09:10:30 OCA PAD AMENDMENT - PROJECT HEADER INFORMATION 09/14/90

Active

Project #: G-35-657 Cost share #: G-35-396 Rev #: 1
Center # : 10/24-6-R6833-0A0 Center shr #: 10/22-1-F6833-0A0 OCA file #:
Work type : RES
Contract#: NA89AA-D-AC225 Mod #: 1 Document : GRANT
Prime #: Contract entity: GTRC

Subprojects ? : N
Main project #:

Project unit: E & A SCI Unit code: 02.010.140
Project director(s):
JUSTUS C G E & A SCI (404)894-3890

Sponsor/division names: US DEPT OF COMMERCE / NATL OCEAN & ATMOS ADM
Sponsor/division codes: 110 / 004

Award period: 891015 to 910930 (performance) 911230 (reports)

Sponsor amount	New this change	Total to date
Contract value	52,842.00	102,801.00
Funded	52,842.00	102,801.00
Cost sharing amount		16,250.00

Does subcontracting plan apply ?: N

Title: SATELLITE TECHNIQUES FOR SURFACE UV RADIATION BUDGET DETERMINATION

PROJECT ADMINISTRATION DATA

OCA contact: Brian J. Lindberg 894-4820

Sponsor technical contact

DR. J. MICHAEL HALL
(301)443-8415

U.S. DEPARTMENT OF COMMERCE, NOAA
6010 EXECUTIVE BLVD., ROOM 825
ROCKVILLE, MARYLAND 20852

Sponsor issuing office

SUSAN E. HARTY
(301)427-2922

U.S. DEPARTMENT OF COMMERCE, NOAA
GRANTS MANAGEMENT DIV., ATTN: OA321
1325 EAST-WEST HWY, SSMCE, 5TH FLOOR
SILVER SPRING, MARYLAND 20910

Security class (U,C,S,TS) : U
Defense priority rating : N/A
Equipment title vests with: Sponsor
HOWEVER, NONE PROPOSED OR ANTICIPATED.

ONR resident rep. is ACO (Y/N): N
N/A supplemental sheet
GIT X

Administrative comments -
AMEND. NO. 1 ADDS $52,842 IN NEW FUNDS AND EXTENDS PROJECT THROUGH SEPTEMBER 30, 1991 (2ND YR 10/15/90-9/30/91). CHANGE ALSO MADE TO ISSUING OFFICE.

SEP 1990
RECEIVED
SUPPORT SERVICE
OCA

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 01/28/92

Project No. G-35-657 Center No. 10/24-6-R6833-0A0

Project Director JUSTUS C G School/Lab E & A SCI

Sponsor US DEPT OF COMMERCE/NATL OCEAN & ATMOS ADM

Contract/Grant No. NA89AA-D-AC225 Contract Entity GTRC

Prime Contract No.

Title SATELLITE TECHNIQUES FOR SURFACE UV RADIATION BUDGET DETERMINATION

Effective Completion Date 910930 (Performance) 911230 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	911212
Final Report of Inventions and/or Subcontracts	Y	
Government Property Inventory & Related Certificate	Y	911015
Classified Material Certificate	N	
Release and Assignment	N	
Other	N	

Comments

Subproject Under Main Project No.

Continues Project No.

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other	N
	N

NOTE: Final Patent Questionnaire sent to PDPI.

G-35-657

SATELLITE TECHNIQUES FOR SURFACE UV RADIATION BUDGET DETERMINATION

C. G. Justus, Principal Investigator

School of Earth and Atmospheric Sciences

Georgia Institute of Technology

Atlanta, GA 30332

January, 1990

QUARTERLY PERFORMANCE REPORT

Report Period: October 15, 1989 - December 15, 1989

PREPARED FOR THE

UNITED STATES DEPARTMENT OF COMMERCE

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Under Grant No. NA89AA-D-AC225

Eileen L. Shea, Technical Monitor

Georgia Tech Project G-35-657

PROGRESS TO DATE

An invited presentation "UV Transfer through Clouds" was made at the 2nd U.S.-Dutch Expert Workshop on UV-B: Measurements, Exposure and Effects, held in Winston-Salem, NC December 10-14, 1989. A summary of that presentation is attached.

In preparation for modifications to our UV radiative transfer models to higher resolution (2 nm or better) in the UV wavelengths, ozone absorption coefficient data from Vigroux (1953) have been analyzed for spectral and temperature variability. High resolution ozone absorption cross section data of Bass and Paur (1985), Paur and Bass (1985), have also been requested.

For the study of Robertson-Berger meter results, data of Scotto et al. (1988) have been requested for time periods which overlap our present data base of Eppley TUVR data and other irradiance, cloud and meteorlogical observations.

For study of the dynamical/synoptic influence on total ozone column, a brief literature survey has been done. Some of the relevant papers identified are Schoeberl and Krueger (1983), Rodgers et al (1986), and Sechrist et al (1986). The video atlas of TOMS ozone data (Chesters and Kreuger, 1989) has been ordered and received.

PLANS FOR THE COMING PERIOD

The improved spectral resolution model for UV-B and UV-A will be completed, including the high resolution absorption cross sections from Vigroux and Bass and Paur.

Analysis of the Robertson-Berger meter data and comparisons with Eppley TUVR will begin.

Study of the dynamical/synoptic influences on ozone column amount will also begin.

A visit to Dr. John DeLuisi in Boulder is being arranged.

REFERENCES

Bass, A.M. and R.J. Paur (1985): "The Ultraviolet Cross-Section of Ozone: I. The Measurements", Proceedings of the Quadrennial Ozone Symposium, Halkidiki, Greece, 3-7 September 1984, C.S. Zerefos and A. Ghazi, eds., 606-610.

Chesters, D. and A.J. Kreuger (1989): "A Video Atlas of TOMS Ozone Data 1978-88", Bull. Amer. Meteorol. Soc., 70(12), 1564-1569.

Paur, R.J. and A.M. Bass (1985): "The Ultraviolet Cross-Sections of Ozone: II. Results and Temperature Dependence", Proceedings of the Quadrennial Ozone Symposium, Halkidiki, Greece, 3-7 September, 1984, C.S. Zerefos and A.Ghazi, eds., 611-616.

Rodgers, E. et al. (1986): "Upper-Tropospheric and Lower-Stratospheric Dynamics Associated with Tropical Cyclones as Inferred from Total Ozone Measurement", Proceedings of 2nd Conf. on Satellite Meteorology, Williamsburg, VA, 382-387.

Schoeberl, M.R. and A.J. Kreuger (1983): "Medium Scale Disturbances in Total Ozone During Southern Hemisphere Summer", Bull. Amer. Meteorol. Soc., 64(12): 1358-1365.

Scotto, J. et al. (1989): "Biologically Effective Ultraviolet Radiation: Surface Measurements in the United States", 1974 to 1985, Science, 239: 762-764.

Sechrist, F.S. et al. (1986): "Ozone, Jet Streaks, and Severe Weather", Proceedings of 2nd Conf. on Satellite Meteorology, Williamsburg, VA, 388-392.

Vigroux, E. (1953): "Contribution a l'Etude Experimentale de l'Absorption de l'Ozone", Annales de Physique, 8: 709-762.

INVITED PRESENTATION AT
2ND U.S.-DUTCH EXPERT WORKSHOP
UV-B: MEASUREMENTS, EXPOSURE AND EFFECTS
Winston-Salem, NC
December 10-14, 1989

<u>Presentation Summary</u>

UV Transfer Through Clouds

C. G. Justus
School of Earth and Atmospheric Sciences
Georgia Institute of Technology
Atlanta, GA 30332-0340

Figures 1 and 2 show the spectral radiative budget (transmitted to the surface, reflected out the top-of-atmosphere, and absorbed within the atmosphere) for wavelengths 290-380 nm for the cases of clear sky (Figure 1) and overcast cloud of optical depth 20 (Figure 2). Clouds not only have a strong affect on the magnitude of the transmittance and reflectance but on the spectral distribution of the radiation budget components as well.

Figures 3-6 show measurements of UV with an Eppley TUVR instrument (300-390 nm response) under clear and cloudy conditions. These figures show that under cloudy conditions a larger fraction of the broadband (300-3000 nm) global irradiance is transmitted as UV irradiance. This increase in UV/Global ratio with increasing cloud optical depth (decreasing global transmittance) is also illustrated by Figure 7.

The effects of monthly average cloudiness, as measured by sunshine duration, on UV surface irradiance is shown in Figure 8. For a given amount of cloudiness there is somewhat more UV (relative to extraterrestrial irradiance on a horizontal surface) in summer (open triangles) than in winter (solid triangles). In part this might be due to the increase in UV with decreasing relative air mass (decreasing solar zenith angle) as seen in Figure 5.

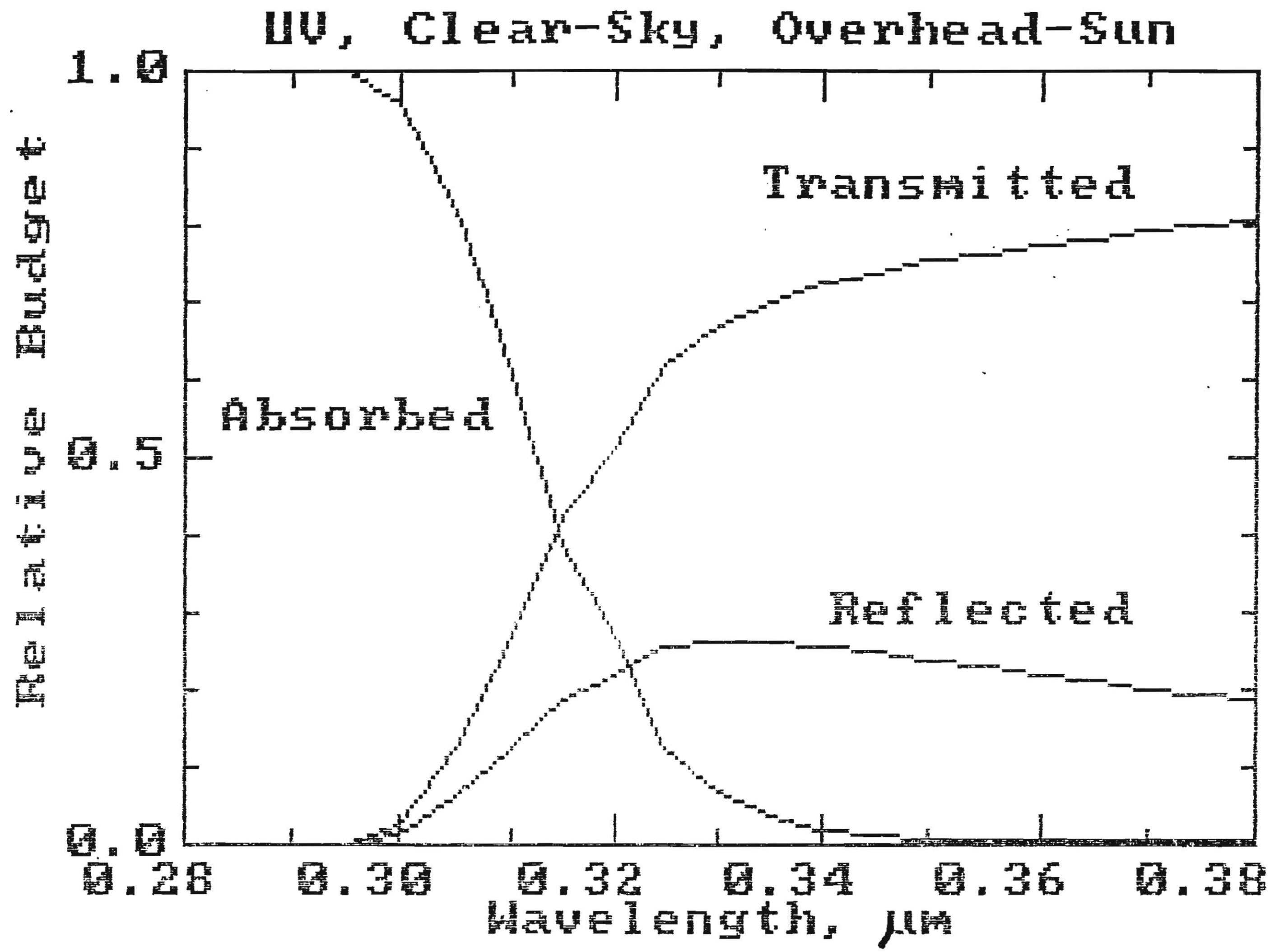

Figure 1. UV spectral energy budget (transmitted to surface, reflected at top of atmosphere and absorbed within atmosphere) for clear sky conditions.

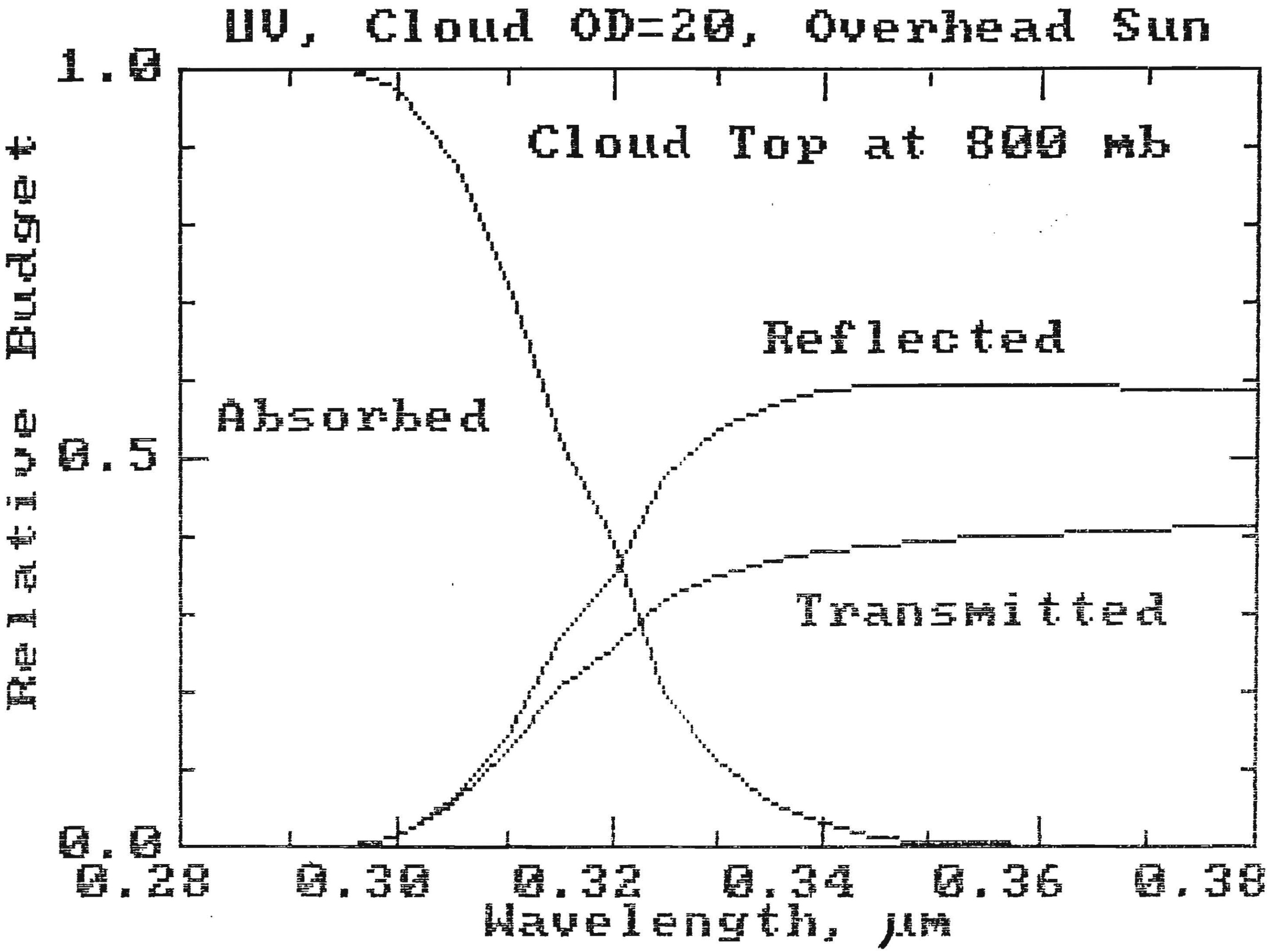

Figure 2. As in Figure 1 for a cloud layer with optical depth 20 (at 500 nm).

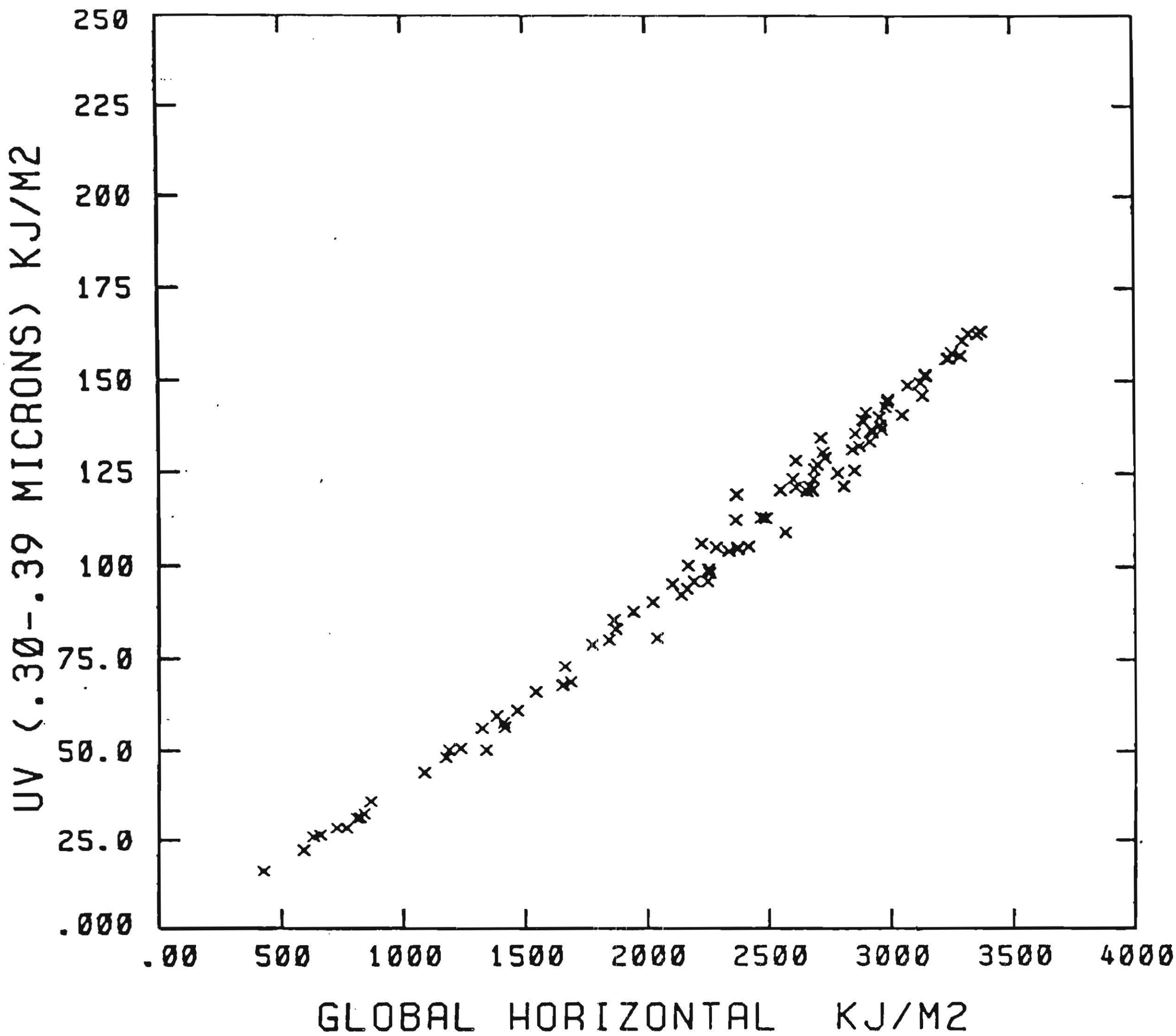

Figure 3. Hourly Ultraviolet (0.30-0.39μ) versus Global for March 1980, Clear Skies.

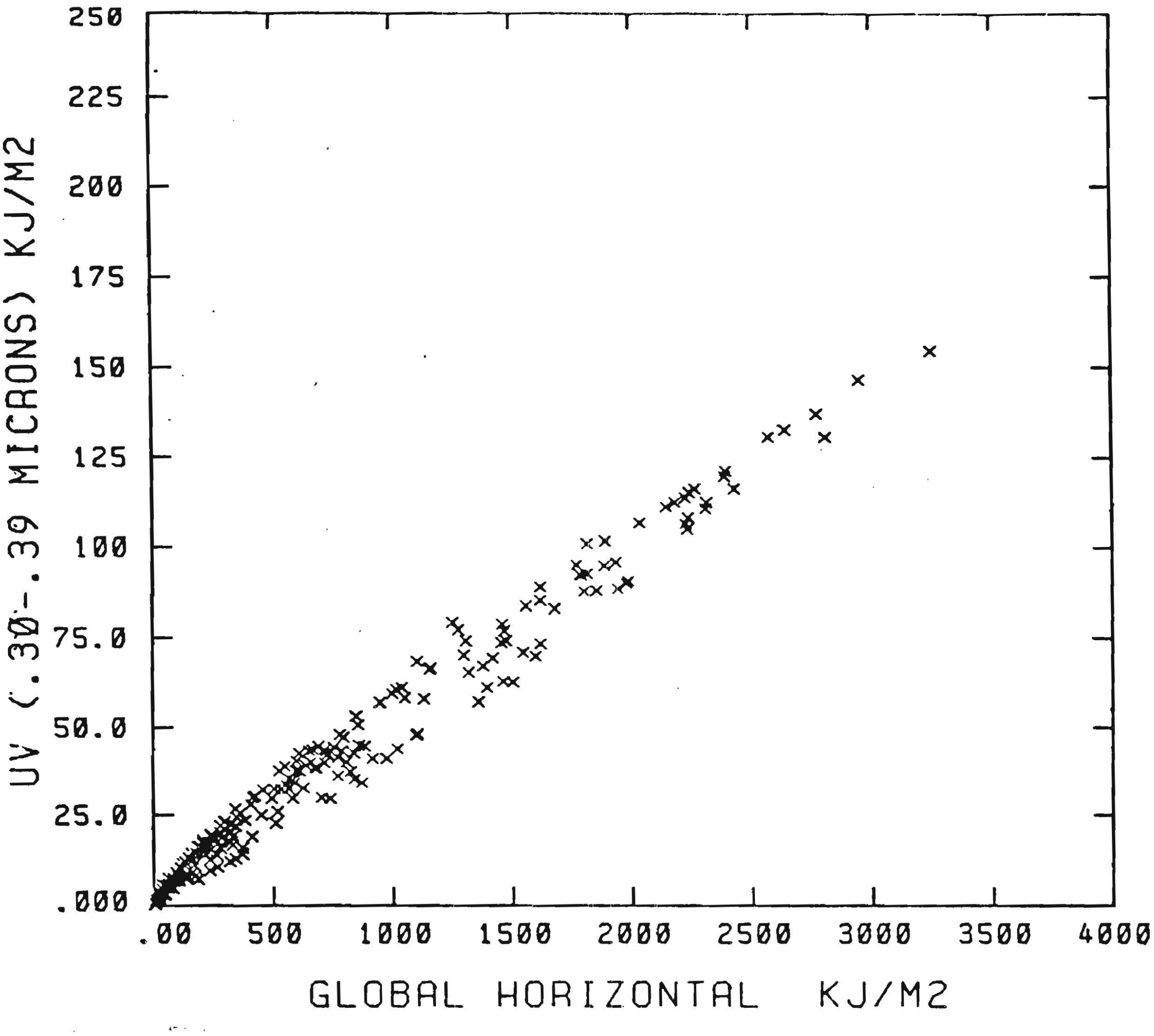

Figure 4. Hourly Ultraviolet (0.30-0.39μ) versus Global for March 1980, Overcast and Partly Cloudy Skies.

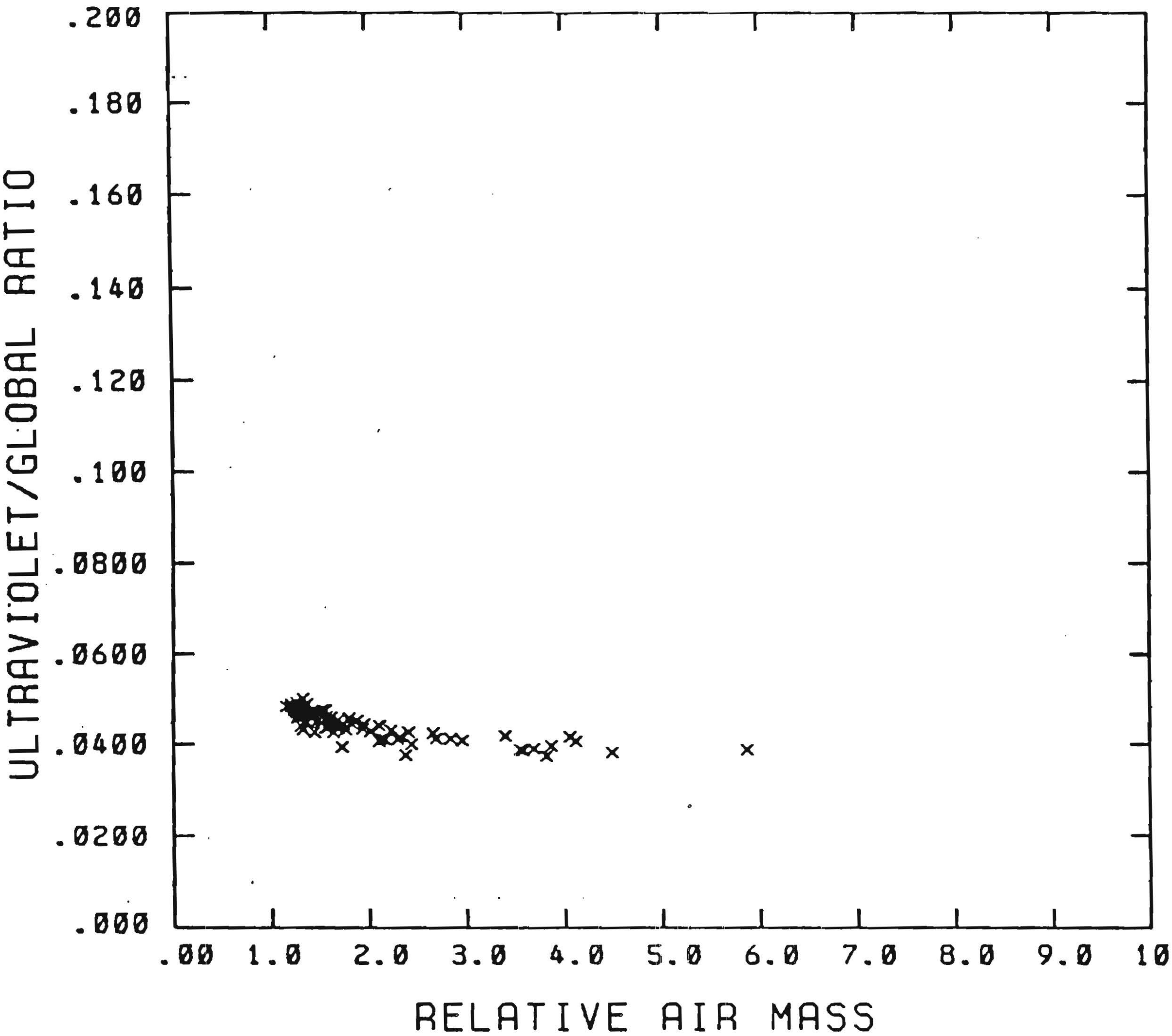

Figure 5. Hourly Ultraviolet (0.30-0.39μ)-to-Global Ratio versus Relative Air Mass for March 1980, Clear Skies.

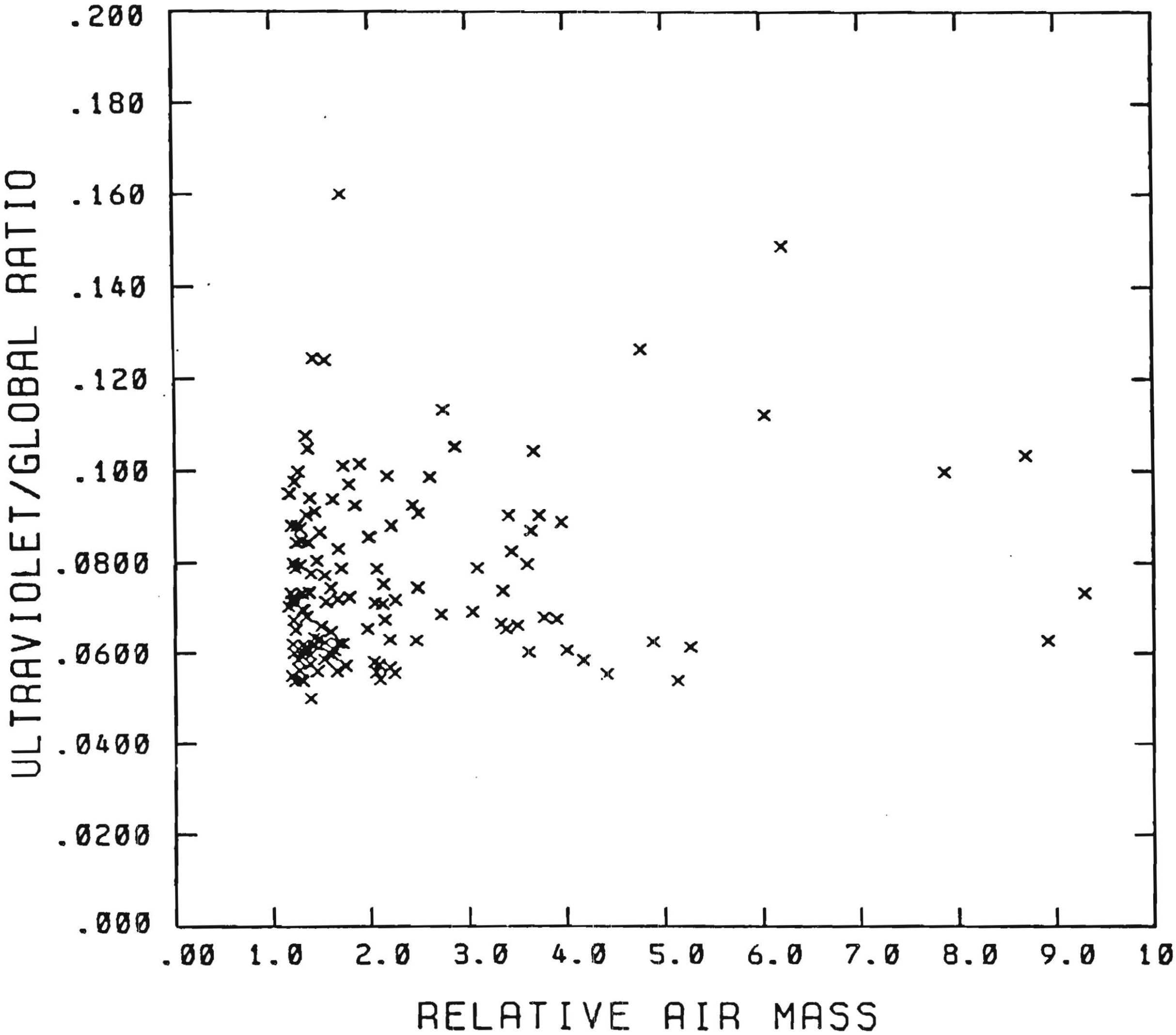

Figure 6. Hourly Ultraviolet (0.30-0.39μ)-to-Global Ratio versus Relative Air Mass for March 1980, Cloudy Skies.

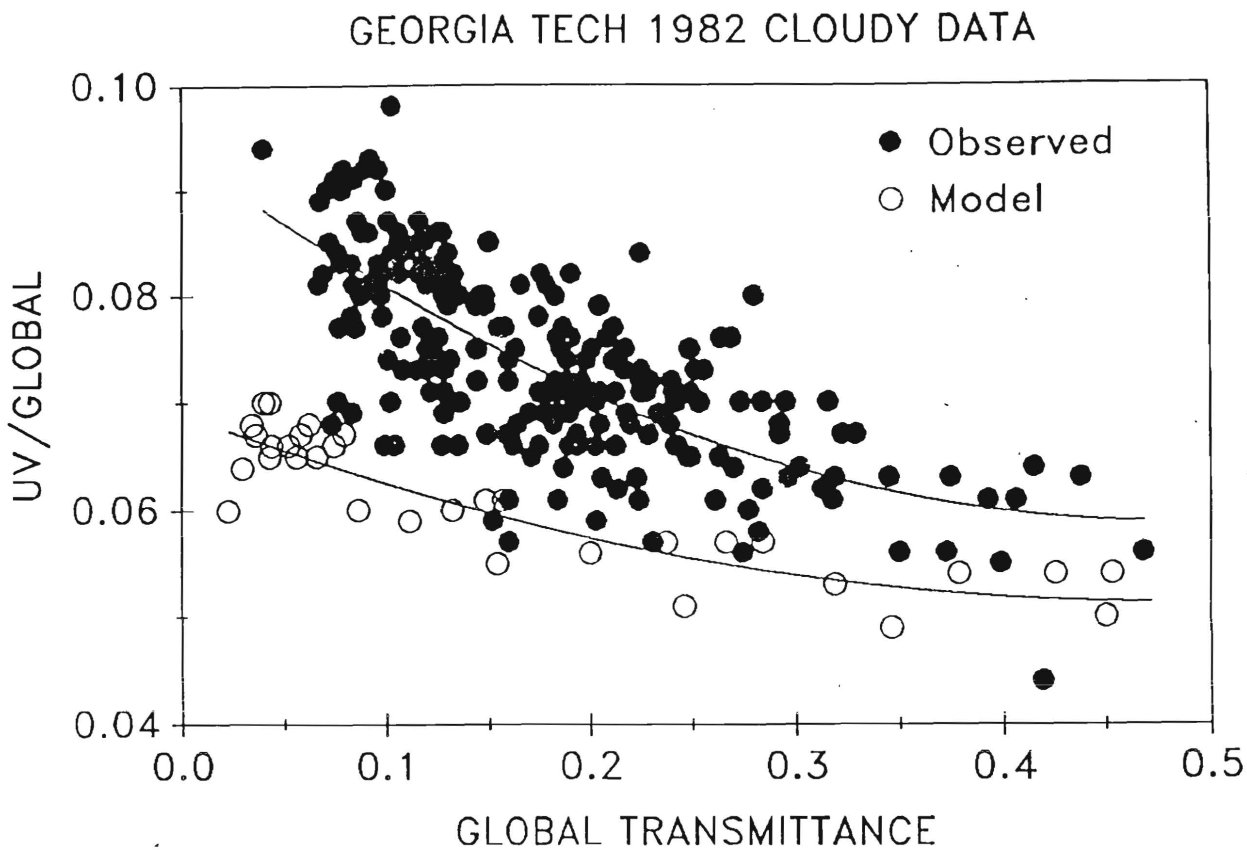

Figure 7. Plot of the ratio of ultraviolet-to-global irradiance versus global transmittance, measured in cloudy conditions during 1982 at the Georgia Tech solar site (•): (o) modeled UV-to-global ratios.

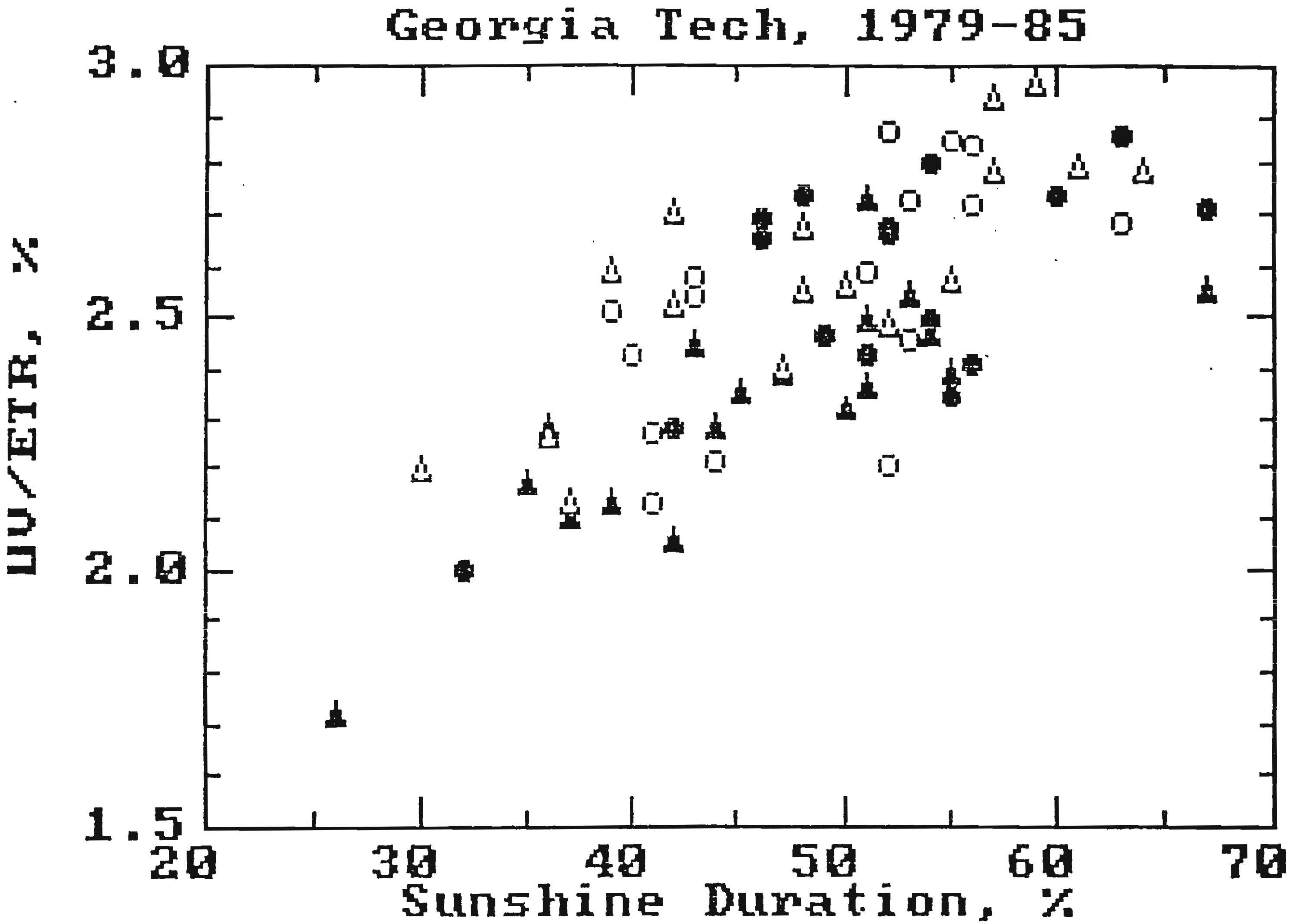

Figure 8. Monthly Average TUVR Ultraviolet/Broad-Band Extraterrestrial versus Monthly Sunshine Duration and Season. Open Circle: Spring; Solid Circle: Fall; Open Triangle: Summer; Solid Triangle: Winter.

G-35-657

SATELLITE TECHNIQUES FOR SURFACE UV RADIATION BUDGET DETERMINATION

C. G. Justus, Principal Investigator

School of Earth and Atmospheric Sciences

Georgia Institute of Technology

Atlanta, GA 30332

April, 1990

QUARTERLY PERFORMANCE REPORT

Report Period: December 15, 1989 - March 15, 1990

PREPARED FOR THE

UNITED STATES DEPARTMENT OF COMMERCE

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Under Grant No. NA89AA-D-AC225

Eileen L. Shea, Technical Monitor

Georgia Tech Project G-35-657

Progress to Date

Half-hourly UVB readings (Robertson-Berger meter counts) have been obtained from Dr. Joseph Scotto of the U.S. Department of Health and Human Services. These data cover the daily interval between 4 am and 8 pm for the period January, 1980 through May, 1983 at the Atlanta Airport and the period June, 1983 through December, 1985 at Emory University in Atlanta. These data will be summarized into hourly values and daily total values for comparison with Eppley TUVR readings (UV-B plus UV-A) hourly data obtained from the Georgia Tech SEMRTS site in Atlanta from the period January, 1980 through October, 1985.

These RB meter and Eppley TUVR data sets will form the basis of surface UV irradiance for the development of our satellite UV irradiance model. Attached, for reference, is a comparison of Georgia Tech UV irradiance measurements compared with those from other SEMRTS university sites for 1981.

For the modeling effort, new 1-nm resolution ozone absorption cross section data by Bass and Paur have been requested but have not yet been received.

Although substantial SBUV satellite data and analysis programs are already on hand for the satellite UV irradiance algorithm development, new SBUV data will be ordered for the period 1979-1985. These data will incorporate the new values for ozone absorption cross sections at the SBUV wavelengths.

Hourly GOES satellite data, also to be used in the satellite UV irradiance algorithm development, have already been merged into the SEMRTS data base.

MEAN DAILY VALUES OF UV RADIATION FOR SUMMER, WINTER AND THE YEAR FOR 8 SITES IN THE USA.

(Kjm^{-2} day^{-1})

Measured by Eppley TUVR
(295-385 μm)

		April-Sept Summer	Oct-March Winter	Annual Value
Fairbanks, Alaska	1980	619	120	369
	1981	626	113	370
Corvallis, Oregon	1981	974	350	662
Davis, California	1981	926	424	675
Honolulu, Hawaii	1981	1117	775	946
Ann Arbor, Michigan	1981	788	368	578
San Antonio, Texas	1981	994	589	792
Atlanta, Georgia	1981	988	572	780
Albany, New York	1981	816	358	587

G-35-657

SATELLITE TECHNIQUES FOR SURFACE UV RADIATION BUDGET DETERMINATION

C. G. Justus, Principal Investigator

School of Earth and Atmospheric Sciences

Georgia Institute of Technology

Atlanta, GA 30332

June, 1990

QUARTERLY PERFORMANCE REPORT

Report Period: March 15, 1990 - June 15, 1990

PREPARED FOR THE

UNITED STATES DEPARTMENT OF COMMERCE

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Under Grant No. NA89AA-D-AC225

Eileen L. Shea, Technical Monitor

Georgia Tech Project G-35-657

Progress to Date

Half-hourly UVB readings (Robertson-Berger meter counts) have been obtained from Dr. Joseph Scotto of the U.S. Department of Health and Human Services. These data cover the daily interval between 4 am and 8 pm for the period January, 1980 through May, 1983 at the Atlanta Airport and the period June, 1983 through December, 1985 at Emory University in Atlanta. These data are being summarized into hourly values and daily total values for comparison with Eppley TUVR readings (UV-B plus UV-A) hourly data obtained from the Georgia Tech SEMRTS site in Atlanta from the period January, 1980 through October, 1985. These RB meter and Eppley TUVR data sets will form the basis of surface UV irradiance for the development of our satellite UV irradiance model.

For the modeling effort, new ozone absorption cross section data by Bass and Paur, at better than 1-nm resolution, have been obtained from James E. Morris of the National Institute of Standards and Technology. These data, together with high resolution ozone absorption cross section data obtained form the literature (Molina and Molina, 1986; Cacciani et al., 1989) are being processed to the 2 nm resolution being used in our model revision.

A simplified parameterization to represent the temperature dependence of the ozone absorption cross sections has been developed. First the variation of ozone absorption cross section at any wavelength, as a function of local air temperature is represented by a power-law approximation, based on the observed temperature dependence in the Bass and Paur, Molina and Molina, and Cacciani et al. data. This relation is of the form

$$K(T) = K(273)\,(T/273)^{\alpha} \quad . \tag{1}$$

Figure 1 shows the high spectral resolution values for α as a function of wavelength from the Vigroux (1953) data, compared to a low (5-nm) resolution analysis of the exponent for the Bass and Paur data.

To represent the total effective column ozone absorption (per equivalent atmospheric cm of ozone), a parameterization of the form

$$X = K(273)\,(T_1/273)^{\alpha}\,[\,A + B\,(T_1/273) + C\,(T_1/273)^2] \quad . \tag{2}$$

where T_1 is the stratospheric temperature, and the coefficients A, B, and C are functions of the surface temperature, T_0, given by

$$\begin{aligned} A &= 1.09570 + 0.33319\times10^{-3}\,T_0 + 0.48929\times10^{-6}\,T_0^{\,2} \\ B &= -0.48153 + 0.10095\times10^{-2}\,T_0 - 0.34679\times10^{-5}\,T_0^{\,2} \\ C &= 0.35827 - 0.11949\times10^{-2}\,T_0 + 0.28536\times10^{-5}\,T_0^{\,2} \quad . \end{aligned} \tag{3}$$

The total ozone optical depth for absorption of beam irradiance would be X times the total ozone column amount in atmospheric cm.

Substantial SBUV satellite data and analysis programs are already on hand for the satellite UV irradiance algorithm development, including programs to scan the data tapes and select data for a given location and time. New SBUV data has been ordered and received for the period 1979-1985. These data incorporate the new values for ozone absorption cross sections at the SBUV wavelengths. Processing of the SBUV data has begun. The SBUV radiance data will be extracted which matches the location of the Georgia Tech SEMRTS site. Hourly GOES satellite data, also to be used in the satellite UV irradiance algorithm development, have already been merged into the SEMRTS data base for the future algorithm development.

REFERENCES

Cacciani, M., et al. (1989): "Absolute Determination of the Cross Sections of Ozone in the Wavelength Region 339-355 nm at Temperatures 220-293 K", J. Geophys. Res., 94(D6), 8,485-8,490.

Molina, L. T. and M. J. Molina (1986): "Absolute Absorption Cross Sections of Ozone in the 185- to 350-nm Wavelength Range", J. Geophys. Res., 91(D13), 14,501-14,508.

Vigroux, P. E. (1953): "Contribution a l'Etude Experimentale de l'Absorption de l'Ozone", Ann. de Geophysique, 8, 709-761.

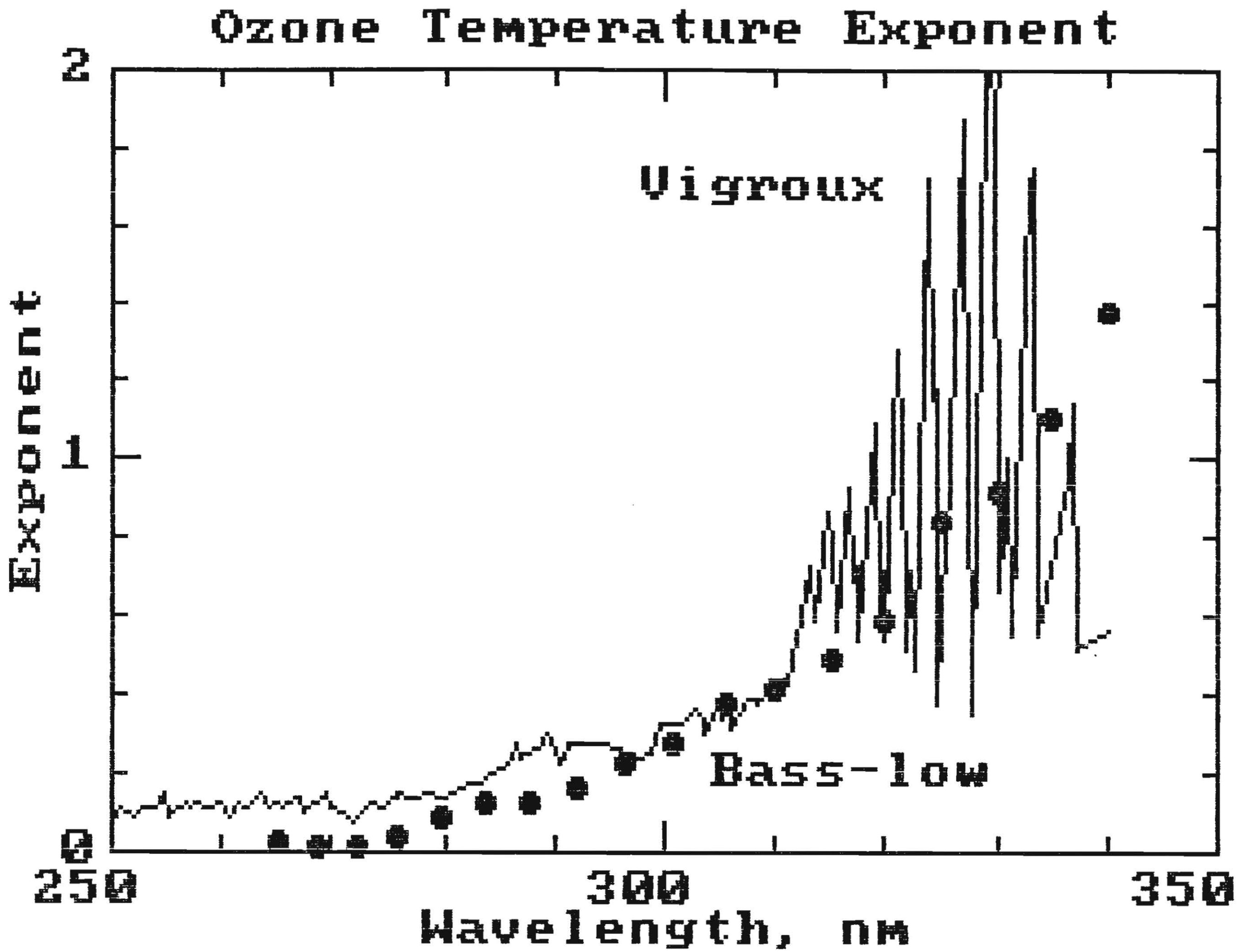
Ozone Temperature Exponent
Vigroux
Bass-low
Exponent
Wavelength, nm
2
1
0
250
300
350

Figure 1

G-35-657

SATELLITE TECHNIQUES FOR SURFACE UV RADIATION BUDGET DETERMINATION

C. G. Justus, Principal Investigator

School of Earth and Atmospheric Sciences

Georgia Institute of Technology

Atlanta, GA 30332

November, 1990

QUARTERLY PERFORMANCE REPORT

Report Period: July 1, 1990 - September 30, 1990

PREPARED FOR THE

UNITED STATES DEPARTMENT OF COMMERCE

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Under Grant No. NA89AA-D-AC225

Eileen L. Shea, Technical Monitor

Georgia Tech Project G-35-657

PROGRESS TO DATE

UV Measurement Study Results

Two recent reports have presented what appears to be conflicting evidence concerning the temporal change of surface UVB (280-320 nm) irradiance in response to possible long-term stratospheric ozone depletion. Scotto et al. (1988) reported downward trends in UVB irradiance between 1974 and 1985, as measured at several ground-level monitoring sites across the United States. These authors concluded that "meteorological, climatic, and environmental factors in the troposphere may play a greater role in attenuating UVB radiation than was previously suspected". Some factors which could possibly explain the results observed by Scotto et al. are: (1) increased reflectance of UVB, before it reaches the surface, due to an increase in cloud amount, or (2) increased reflection and/or absorption of UVB by increasing amounts of tropospheric aerosols. Unfortunately, Scotto et al. did not report any observations of trends in cloud fraction or aerosol amount at their measurement sites, nor did they separate their UVB data into clear-sky and cloudy-sky observations in order to examine these two possible effects.

In contrast to the results of Scotto et al., Blumthaler and Ambach (1990) report an increase in UVB surface irradiance, at the rate of about 1 percent per year, between 1981 and 1989, as measured at a site in the Swiss Alps. Blumthaler and Ambach restricted their analysis to cloudless days, in order to remove cloud effects on the data. Although these two results appear to contradict one another, there are several possible explanations which would render them consistent: (1) A downward trend in UVB irradiance throughout the late 70s and early 80s, may have reversed itself in the late 80s; (2) The Alpine measurements, taken above much of the tropospheric aerosols, may indicate a UVB increase due to decreasing stratospheric ozone, while the U.S. results may indicate that cloud and aerosol effects more than offset this ozone-UVB response; (3) It is possible that one or the other (or both) sets of observations may suffer from calibration shifts in the instruments during the course of the observation period. Although the instrument used in the Scotto et al. and the Blumthaler and Ambach studies, the Robertson-Berger meter, has been characterized and calibrated by DeLuisi and Harris (1983), the potential for its drift in calibration over extended (multi-year) observational programs has not been well documented.

A measurement study has been done, using data from Atlanta, GA, for the years 1980-1983, to help clarify which of these possible explanations may most nearly apply. This study used both Robertson-Berger (RB) meter data and data from an Eppley TUVR instrument. Unlike the RB meter, the TUVR instrument responds mostly to the UVA (320-400 nm) part of the spectrum. Relative filter factors for the RB meter and the TUVR are shown in Figure 1. The RB filter information was taken from Machta and Hass (1978), and the TUVR filter data were obtained with the instrument, from the Eppley Laboratory, Inc. The RB meter was operated in Atlanta, as part of the same National Cancer Institute network, reported on by Scotto et al. (1988). The TUVR was operated on the Atlanta campus of the Georgia Institute of Technology, as part of the Department of Energy-sponsored Solar Energy Meteorological Research and Training Site (SEMRTS) program (Paris and Justus, 1988).

Figure 2 shows results for monthly-average daily total irradiance from the RB meter (in RB counts) and the TUVR (in kJ/m^2). The TUVR irradiances are expressed in kJ/m^2, with the use of a calibration factor obtained from the Eppley Laboratory, as adjusted by comparison of the Atlanta TUVR against a travelling standard TUVR, operated under the SEMRTS program. RB irradiances are sometimes expressed in "sunburn units" (SU), with 440 counts = 1 SU. Absolute energy flux per SU has been determined for the RB meter, by DeLuisi and Harris (1983), to be a non-linear function of solar zenith angle and total column ozone amount.

The data of Figure 2 show that RB irradiance increases non-linearly as the TUVR irradiance increases. The monthly-average daily total irradiances of this Figure both vary primarily with the seasonal changes in monthly average solar zenith angle. The non-linear relationship exhibited by Figure 2, is therefore an indication that the RB meter and the TUVR respond differently to changes in solar zenith angle. This conclusion is borne out by model studies, reported in the next section of this report.

When the data of Figure 2 are separated by year, it is seen that the RB/TUVR ratio is approximately 20% larger for years 1980-81 than for years 1982-83. Data in Tables 1-3 present evidence to explain this temporal trend in RB/TUVR ratio.

Table 1 presents data on the average, daily-total, broadband (0.3 - 4 μm) irradiance, as measured at the SEMRTS station in Atlanta, with data separated according to days which were clear or overcast, as well as days under all cloud conditions. Only days with complete measurements of all three irradiance components (global, RB meter and TUVR) were considered. Table 1 also shows, by year, the total number of days analyzed in the cloudy, clear and all-sky categories, along with the annual-average sunshine duration for each year, as measured by an automatic sunshine duration recorder (Paris and Justus, 1988). The hourly sunshine duration readings for each day were used in the separation of the data into clear-day and overcast-day subsets.

Table 2 shows average daily total irradiances from the RB meter (counts) and the TUVR (kJ/m^2), by year, for the same data set as in Table 1. Data from Tables 1 and 2 are used to produce values for the ratios RB/Global and TUVR/Global. The value of reducing RB data to RB/Global ratio has been demonstrated by Paris and Justus (1988) and Blumthaler and Ambach (1990). The results of Table 3 show that both RB/Global and TUVR/Global ratios increase under the influence of clouds. This result is consistent with the earlier results of Paris and Justus and Blumthaler and Ambach.

Figure 3 presents the RB/Global ratios of Table 3, normalized by the four-year average value of this ratio (also shown in Table 3). This Figure shows that, for clear-sky, and overcast-sky data, as well as for all-sky data, the RB/Global ratio decreased by about 10% over the course of the four years examined. This result is not inconsistent with the downward trend in RB readings reported by Scotto et al. (1988). However, since virtually the same downward trend is seen in clear-sky data as in cloudy data, the results in Figure 3 appear to rule out increasing atmospheric aerosols as a possible cause for this downward trend. Based on Table 1, the years 1982-83 had larger average cloud fraction (smaller sunshine duration) than did the years 1980-81. Therefore the effects of increasing cloud fraction to cause the downward trend in Figure 3 cannot yet be ruled out.

A similar plot of TUVR/Global ratio, normalized by the four-year average value of this ratio, is shown in Figure 4. In contrast to the RB/Global ratio, the TUVR/Global ratio increases by about 10% over the course of the four years studied. This increase, of course, cannot be explained by the observed increase in cloud fraction during the later years of the study.

Model studies (presented in the next section) verify that the TUVR response to ozone changes is very small, so the observed increase in TUVR readings cannot be attributed to decreases in ozone amount. Therefore, the observed decrease in RB/TUVR ratio by about 20%, shown in Figure 2, is due to a decrease of about 10% in measured RB irradiance, accompanied by about a 10% increase in measured TUVR irradiance. The fact that these respective decreases and increases are similar for clear-sky, cloudy-sky and all-sky observations, indicates that both temporal trends are due to calibration drift of the respective instruments (i.e. about 2.5% per year drift, downward for the RB meter and upward for the TUVR).

These results indicate that the observed downward trends in UVB reported by Scotto et al. (1988) may be due to calibration shifts in the RB meters used. The upward trends in UVB irradiance reported by Blumthaler and Ambach (1990) are also rendered suspect due to the possibility of a calibration shift in the opposite direction (as seen in the TUVR results here). Therefore, until instruments are developed and employed for which calibrations can be maintained better than the RB meter and TUVR, trends of UVB and UVA irradiance of the order of 1-2% per year cannot be attributed to changes in stratospheric ozone in an unambiguous fashion.

UV Modeling Study Results

In order to better understand the response of the RB meter and TUVR to the effects of solar zenith angle, ozone, aerosols and clouds, and to serve as the basis for the proposed method for determining surface UV irradiance from satellite observations, a spectral radiative transfer model has been adapted for use in simulating the response of the RB meter and TUVR. This model, a variant of the delta-Eddington model described by Paris and Justus (1988), has been modified to work at 1 nm spectral resolution, and to utilize ozone absorption coefficients determined from averaging the data of Bass and Paur (1985; also Paur and Bass, 1985), Molina and Molina (1986) and Cacciani et al. (1989). The model uses spectral filter factors for the RB meter and TUVR as given in Figure 1, and integrates across the respective spectral intervals of the instruments, in 1 nm spectral steps.

To calibrate the model versus the observations, a set of 18 clear days in March, May and December, 1981 were analyzed and modeled. The hourly and daily data in this selected set span a wide range of solar zenith angles (daily averages 14° to 57°), ozone column amounts (0.28 cm to 0.44 cm) and aerosol optical depths (0.12 to 0.29). The measured TUVR irradiances were found to be linearly related to the modeled TUVR irradiances, with the relation

$$\mathrm{TUVR(measured)} = 1.575\ \mathrm{TUVR(modeled)} \quad . \tag{1}$$

Because of uncertainties in the absolute transmittance of the TUVR filter, and other instrument calibration uncertainties, the fact that the coefficient in this relationship differs significantly from 1 is not considered significant.

For the RB meter, a non-linear calibration relating the modeled values to observed values was found, given by

$$R = 95.93\ M + 15.141\ M^2 \quad , \qquad (2)$$

where R is the measured hourly RB meter irradiance (in counts) and M is the modeled hourly RB meter irradiance in J/m^2. Although this calibration is non-linear, the average energy flux per sunburn unit over the range of measured values in the calibration data set is about 2.6 $J\ m^{-2}$ / SU (26 $mJ\ cm^{-2}$ / SU), a value not inconsistent with results observed for the RB meter by DeLuisi and Harris (1983).

Using the calibrations of equations (1) and (2), Figures 5 and 6 show comparisons between measured and modeled hourly RB meter and TUVR irradiance versus time of day for May 2 and December 20, 1981. The agreement between measured and modeled values demonstrated by these two Figures is considered to be satisfactory. Comparison of Figures 5 and 6 shows that, as the time of day changes, the RB meter irradiances drop more quickly with increasing solar zenith angle than is the case with the TUVR irradiances. This result explains the non-linear relationship between RB meter and TUVR irradiances seen in Figure 2. That is, as monthly average solar zenith angles increase from summer to winter, the RB meter values drop at a faster rate than do the TUVR irradiances.

To examine the modeled and measured sensitivity to ozone changes, a sequence of clear-sky data in December 1981 (during which the ozone column amount ranged from about 0.28 cm to about 0.44 cm) was examined. Figure 7 shows results for the measured and modeled RB meter irradiances at the solar noon hour on these days. The solid line in Figure 7 is the observed ozone sensitivity of the RB meter, as determined by DeLuisi and Harris (1983) [a 1.24 percent change in RB meter irradiance for every 1% change in ozone column amount].

Results in Figure 8 demonstrate that the ozone sensitivity for the TUVR measured and modeled values is very small, but with decreasing irradiance for increasing ozone amount. Figure 8 shows values for the measured and modeled daily total TUVR irradiance, with the line indicating a quadratic best fit to the model results. Again, the agreement between the measured and model results is considered to be satisfactory.

Measured and modeled daily total irradiances for all 18 clear days used in the calibration study are shown in Figures 9 (RB meter) and 10 (TUVR). These figures show that, with the model calibrations given in equations 1 and 2, the measured and modeled values follow closely the one-to-one lines for both the RB meter and TUVR results. Thus, for clear-sky conditions, the spectral model has been demonstrated to account adequately for changes in solar zenith angle, ozone amount and aerosol amount. Further studies are planned, in order to compare the model and measured RB meter and TUVR irradiances under cloudy conditions.

Acknowlegments

Sincere thanks are expressed to Dr. Joseph Scotto, of the National Cancer Institute, for supplying the Robertson-Berger meter data for Atlanta, to Dr. James E. Norris, of the National Institute of Standards and Technology, for supplying the Bass and Paur ozone absorption coefficient data, and to Dr. John DeLuisi, for helpful discussion and correspondence concerning the characterization of the Robertson-Berger meter.

REFERENCES

Bass, A.M. and R.J. Paur (1985): "The Ultraviolet Cross-Section of Ozone: I. The Measurements", Proceedings of the Quadrennial Ozone Symposium, Halkidiki, Greece, 3-7 September 1984, C.S. Zerefos and A. Ghazi, eds., 606-610.

Blumthaler, M., and W. Ambach (1990): "Indication of Increasing Solar Ultraviolet-B Radiation Flux in Alpine Regions", Science, 248, 206-208.

Cacciani, M. et al. (1989): "Absolute Determination of the Cross Sections of Ozone in the Wavelength Region 339-355 nm at Temperatures 220-293 K", J. Geophys. Res., 94(D6): 8485-8490.

DeLuisi, J.J. and J.M. Harris (1983): "A Determination of the Absolute Radiant Energy of a Robertson-Berger Meter Sunburn Unit", Atmos. Environ., 17(4): 751-758.

Machta, L. and W.A. Hass (1978): "Summary of Discussion of UV-B from the Robertson-Berger (R/B) Sunburn Meter Network", unpublished manuscript, presented at Climatic Impact Assessment Program meeting, September 22.

Molina, L.T. and M.J. Molina (1986): "Absolute Absorption Cross Sections of Ozone in the 185- to 350-nm Wavelength Range", J. Geophys. Res., 91(D13): 14,501-14,508.

Paris, M.V. and C.G. Justus (1988): "A Cloudy-Sky Radiative Transfer Model Suitable for Calibration of Satellite Sensors", Remote Sens. Environ., 24: 269-285.

Paur, R.J. and A.M. Bass (1985): "The Ultraviolet Cross-Sections of Ozone: II. Results and Temperature Dependence", Proceedings of the Quadrennial Ozone Symposium, Halkidiki, Greece, 3-7 September, 1984, C.S. Zerefos and A.Ghazi, eds., 611-616.

Scotto, J. et al. (1989): "Biologically Effective Ultraviolet Radiation: Surface Measurements in the United States", 1974 to 1985, Science, 239: 762-764.

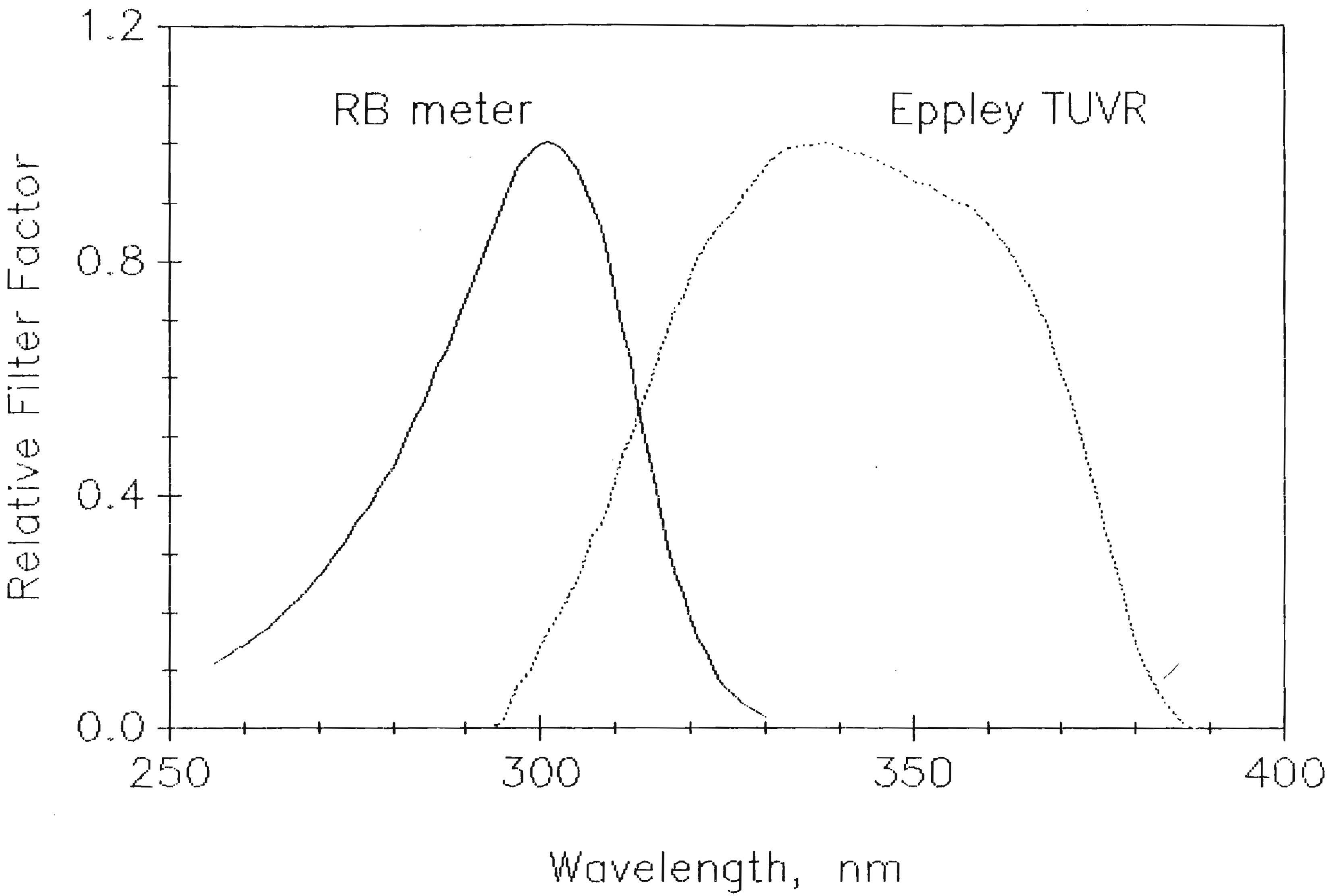

Figure 1 - Relative filter factors for the Robertson-Berger (RB) meter and the Eppley TUVR instruments.

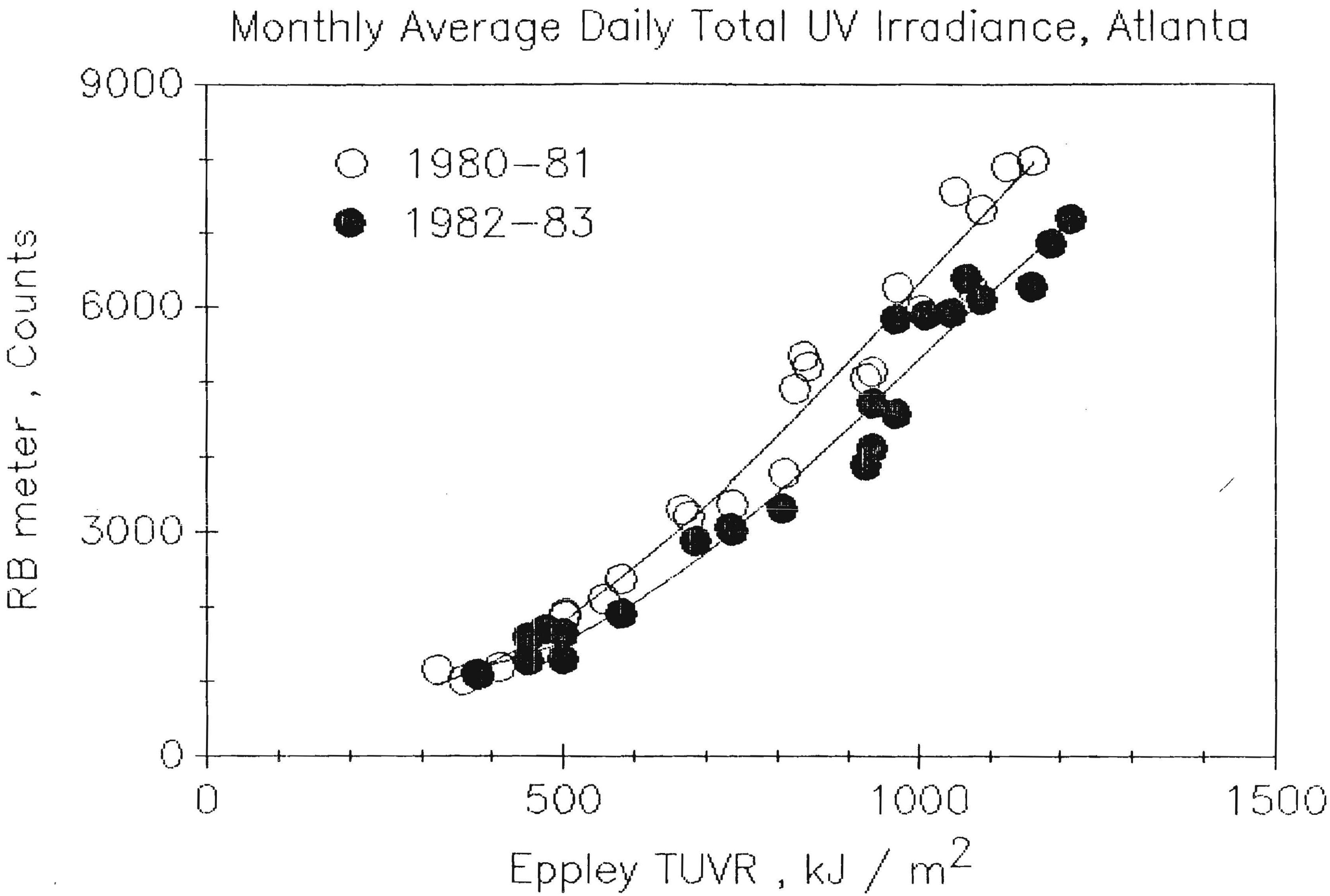

Figure 2 - Observed monthly averaged, daily total UV irradiances observed in Atlanta, from the RB meter and TUVR. Open circles are for months in 1980-81; solid dots are for months in 1982-83.

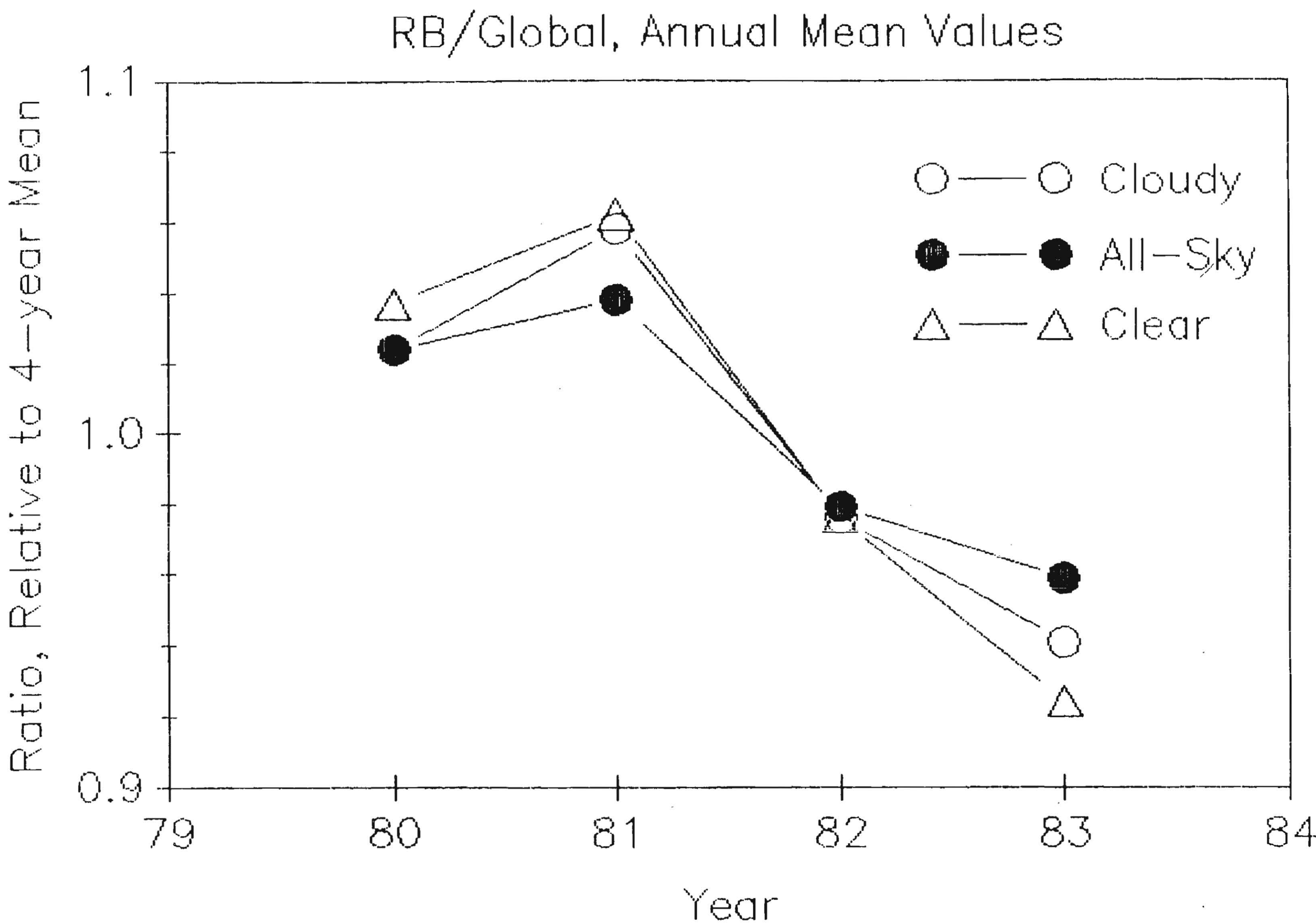

Figure 3 - Trend in RB/Global irradiance ratio (normalized by the 4-year average value of this ratio) for years 1980-83. Triangles are for clear-sky days; open circles are for overcast days; solid dots are all-sky data.

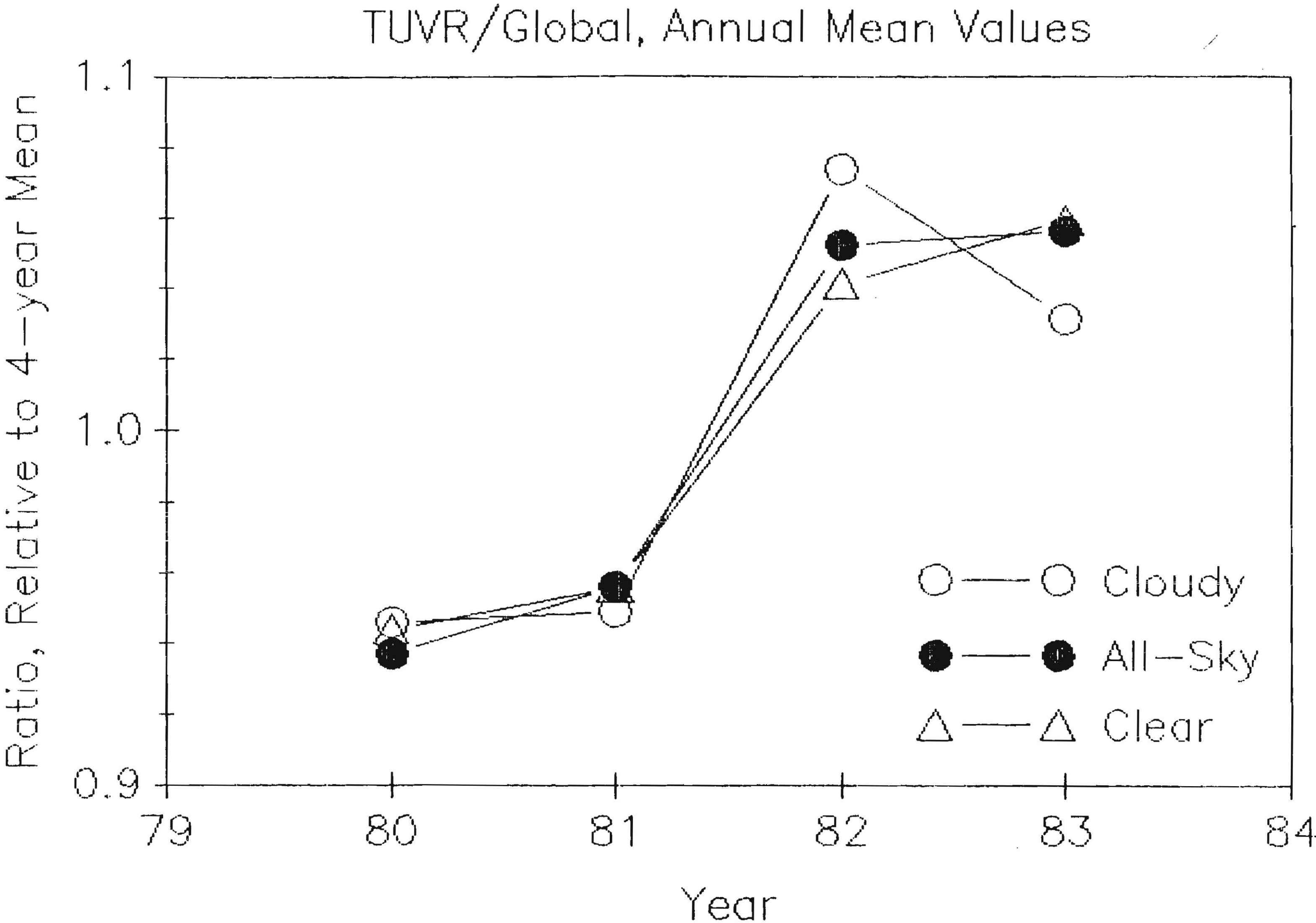

Figure 4 - Trend in TUVR/Global irradiance ratio (normalized by the 4-year average value of this ratio) for years 1980-83. Triangles are for clear-sky days; open circles are for overcast days; solid dots are all-sky data.

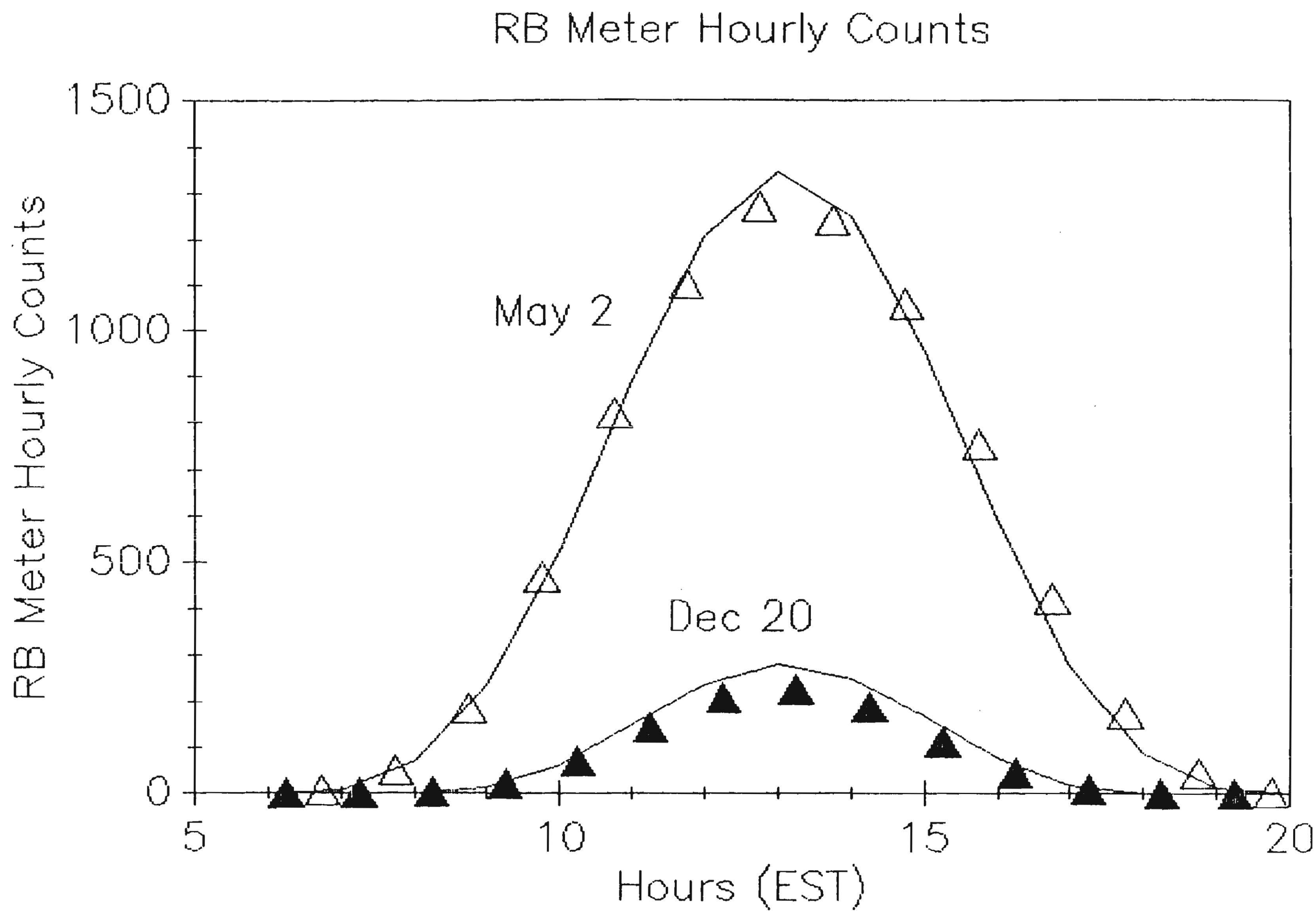

Figure 5 - Observed (symbols) and modeled (lines) values of RB meter hourly irradiances for clear days May 2 and December 20, 1981.

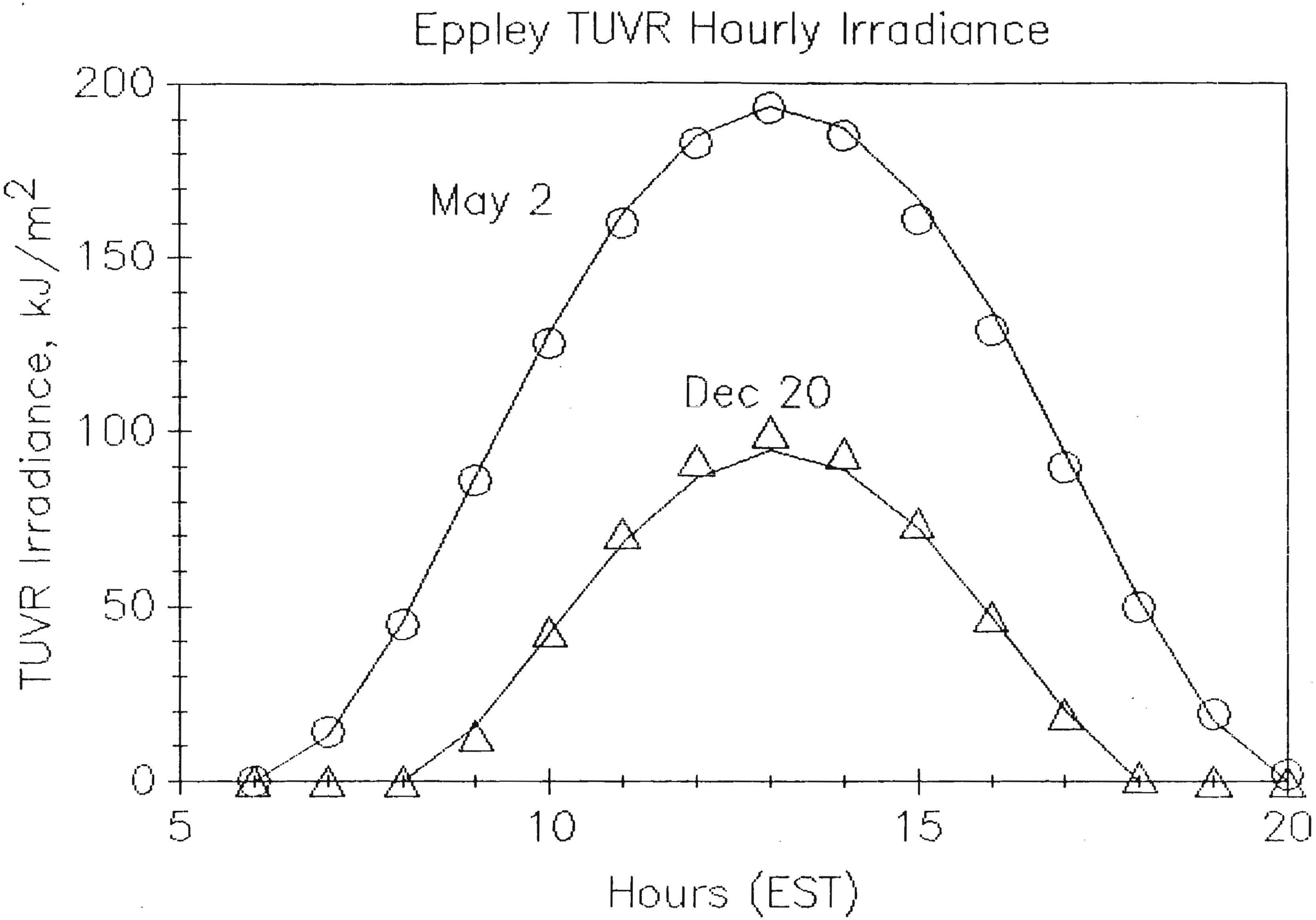

Figure 6 - Observed (symbols) and modeled (lines) values of TUVR hourly irradiances for clear days May 2 and December 20, 1981.

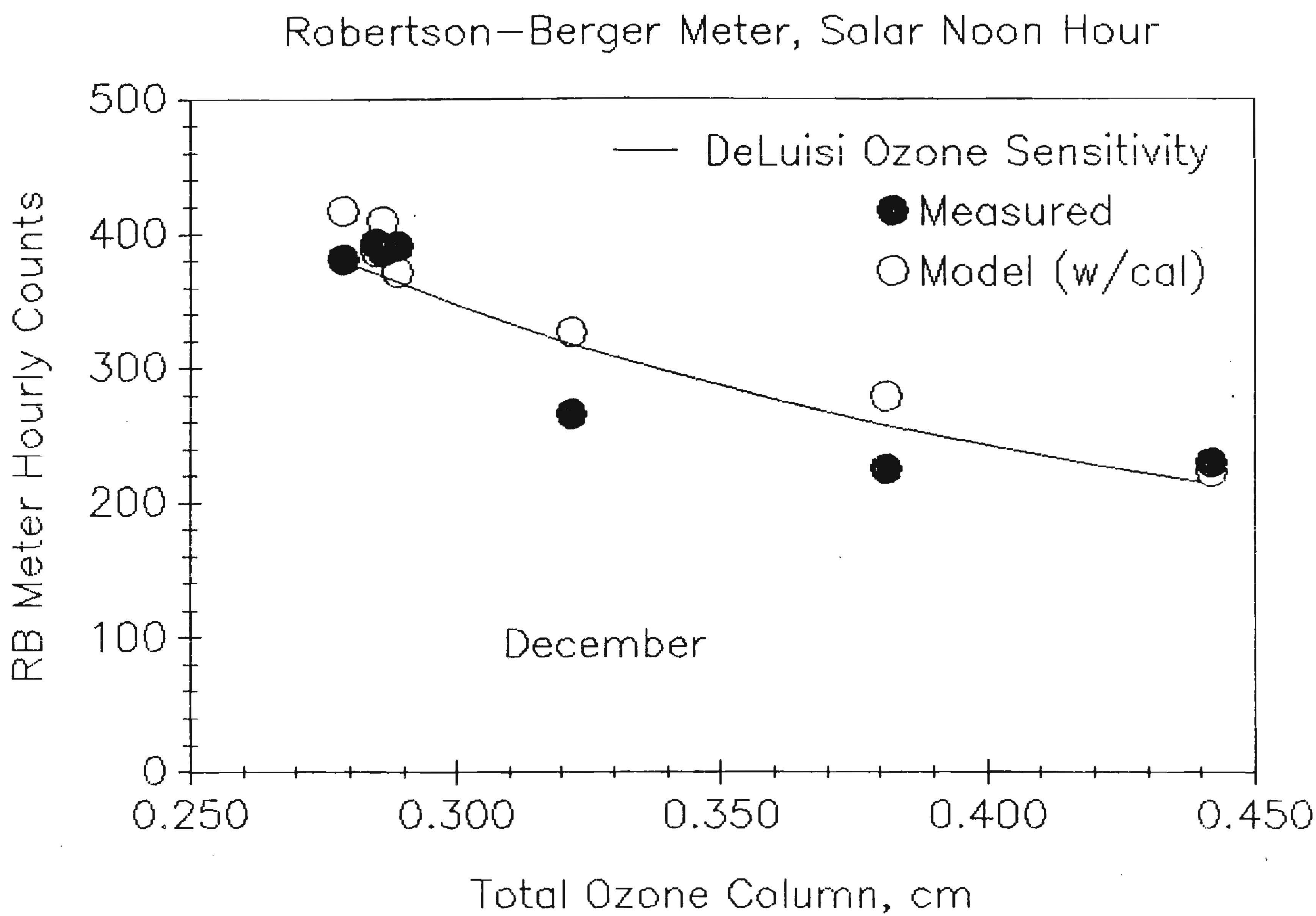

Figure 7 - Observed (solid dots) and modeled (open circles) sensitivity of RB meter hourly irradiances to changes in total column ozone amount. The solid line is the observed ozone sensitivity for the RB meter, determined by DeLuisi and Harris (1983).

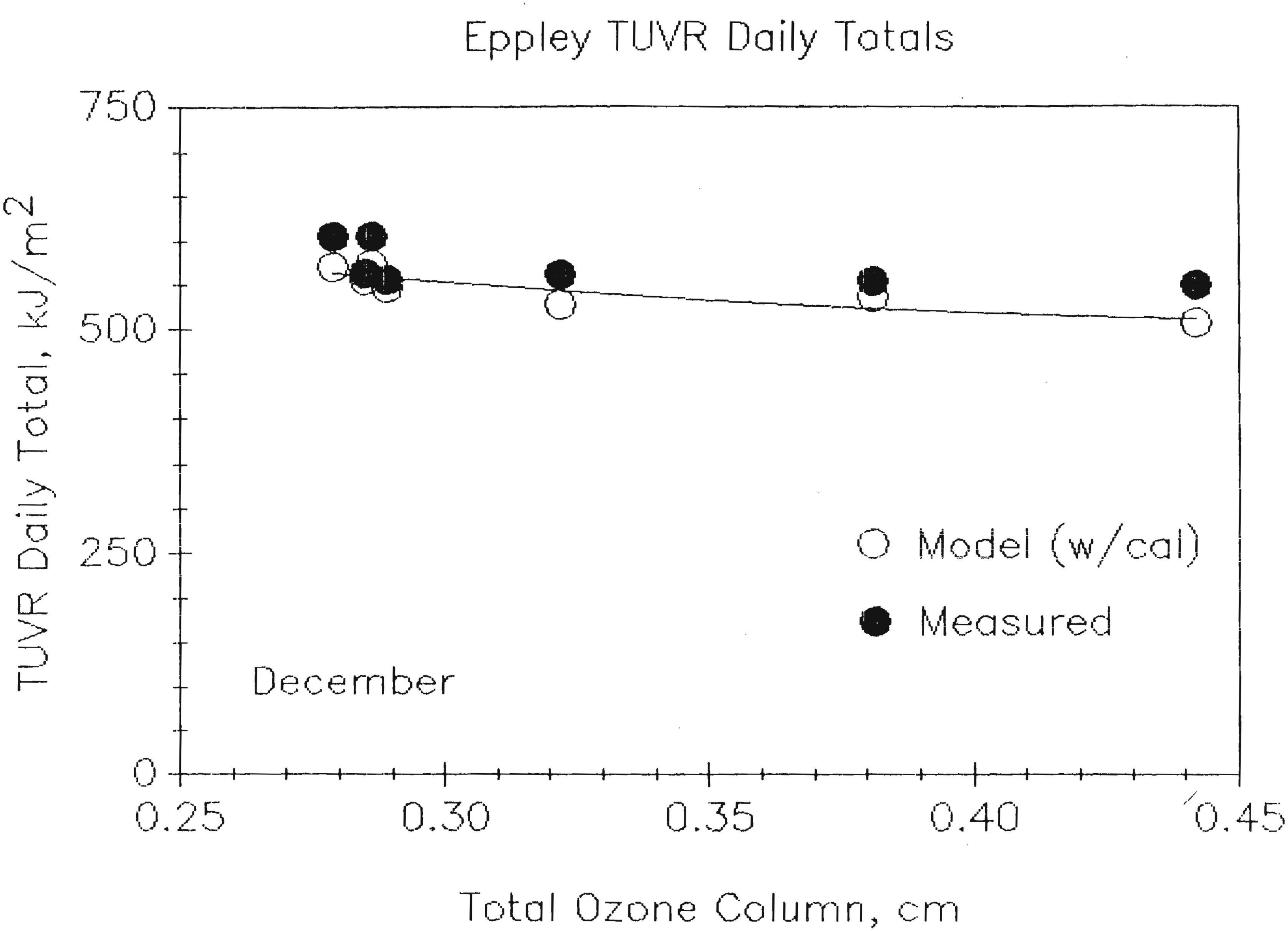

Figure 8 - Observed (solid dots) and modeled (open circles) sensitivity of TUVR daily total irradiances to changes in total column ozone amount. The solid line is the best quadratic fit to the modeled values.

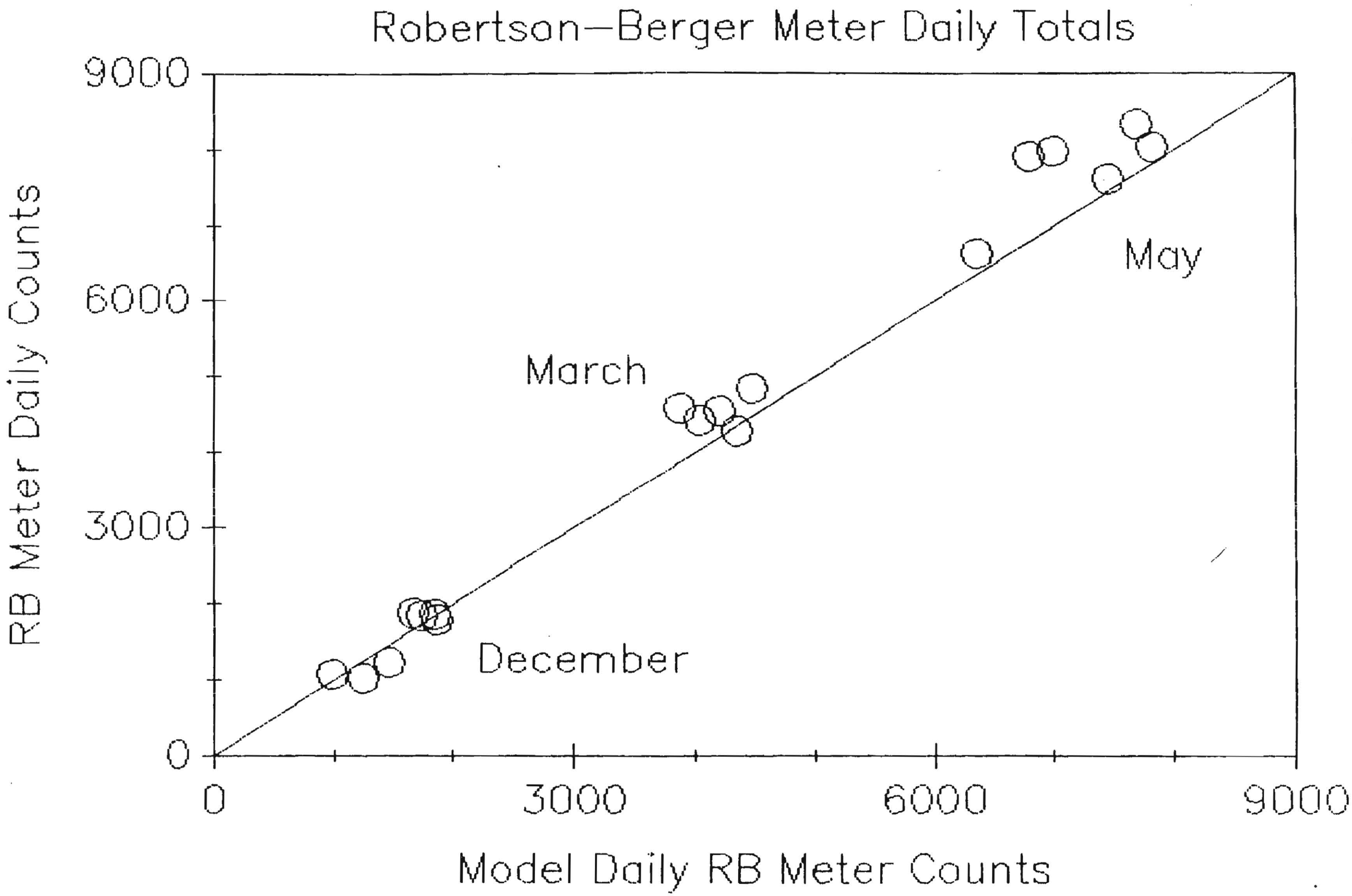

Figure 9 - Observed versus modeled daily total RB meter irradiances. The solid line shows a one-to-one relationship.

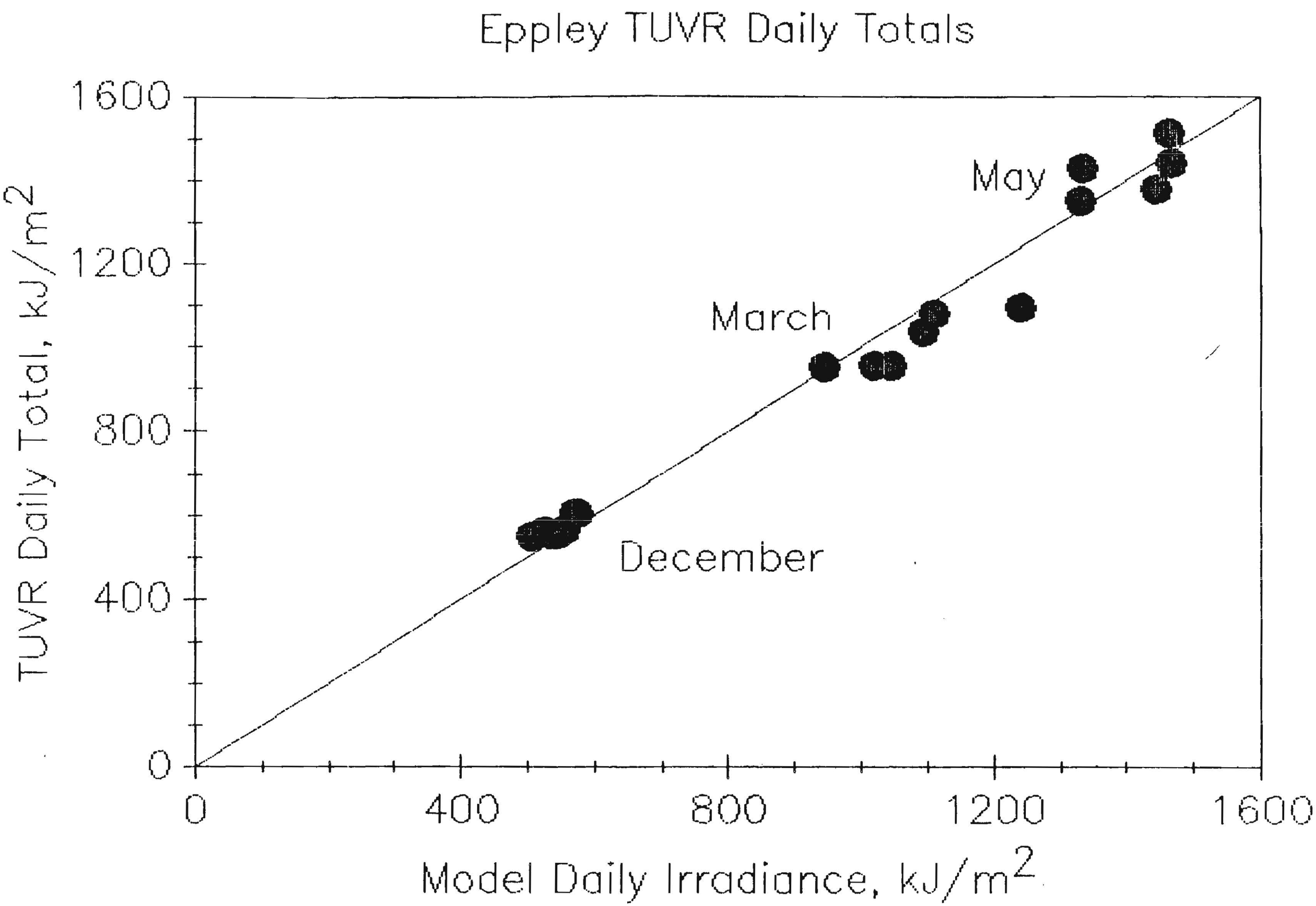

Figure 10 - Observed versus modeled daily total TUVR irradiances. The solid line shows a one-to-one relationship.

Table 1. Average daily total global irradiance, number of days analyzed, and average sunshine duration for years 1980-83.

	Global Daily Irradiance, kJ/m^2			Number of Days Analyzed			Avg. Sunshine
Year	Cloudy	All-Sky	Clear	Cloudy	All-Sky	Clear	Duration %
1980	4104	15,332	18,236	49	243	51	50
1981	4523	15,765	19,183	49	272	54	53
1982	3564	13,886	18,639	57	247	27	44
1983	4380	13,920	17,307	43	201	34	47
AVG	4143	14,726	18,341	50	241	42	49

Table 2. Average daily total Robertson-Berger meter counts, and average daily Eppley TUVR Irradiance for years 1980-1983.

Year	RB Meter Daily Counts			TUVR Daily Irradiance, kJ/m^2		
	Cloudy	All-Sky	Clear	Cloudy	All-Sky	Clear
1980	1200	4127	3940	265	747	839
1981	1367	4303	4246	293	783	894
1982	993	3571	3791	261	759	945
1983	1177	3508	3334	308	764	893
AVG	1184	3877	3828	282	763	893

Table 3. Ratios (RB meter/Global) and (TUVR/Global), from data in Tables 1 and 2.

Year	RB/Global, counts $kJ^{-1}m^2$ Cloudy	All-Sky	Clear	TUVR/Global, unitless Cloudy	All-Sky	Clear
1980	0.2924	0.2692	0.2161	0.0646	0.0487	0.0460
1981	0.3022	0.2729	0.2213	0.0648	0.0497	0.0466
1982	0.2786	0.2572	0.2034	0.0732	0.0547	0.0507
1983	0.2687	0.2520	0.1926	0.0703	0.0549	0.0516
AVG	0.2855	0.2628	0.2084	0.0682	0.0520	0.0487

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G-35-657

SATELLITE TECHNIQUES FOR SURFACE UV RADIATION BUDGET DETERMINATION

C. G. Justus, Principal Investigator

School of Earth and Atmospheric Sciences

Georgia Institute of Technology

Atlanta, GA 30332

January, 1991

QUARTERLY PERFORMANCE REPORT

Report Period: October 1, 1990 - December 31, 1990

PREPARED FOR THE

UNITED STATES DEPARTMENT OF COMMERCE

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Under Grant No. NA89AA-D-AC225

Phillip A. Arkin, Technical Monitor

Georgia Tech Project G-35-657

PROGRESS TO DATE

UV Measurement Study Results

The previous quarterly report outlined measurement studies to date, indicating that both the Eppley TUVR (UV-A) data and Robertson-Berger Meter (UV-B) data suffered a several percent calibration shift over the period of study (1981-1984). The TUVR and RB meter calibration shifts were in opposite directions.

UV Modeling Study Results

The previous quarterly report also showed model results which verify, under clear sky conditions, that there is agreement between the measured and model trends for ozone variation and solar zenith angle variation.

Database from Surface Radiometers and Satellites

A database of surface radiation parameters, and GOES satellite data, described in Table 1, covering the period September, 1982 through October, 1985, has been transferred from our previous computer (a Data General Eclipse minicomputer) to our new IBM RS/6000 workstation system. The RB meter data, provided by Dr Scotto of the National Cancer Institute, have been transferred from IBM PC to the RS/6000 system also. The RB meter data were measured at half-hourly intervals, and covered January, 1980 through May, 1983 from the Atlanta National Weather Service office and June, 1983 through December, 1985 from Emory University in Atlanta.

A timing problem in the half-hourly RB meter data has been noted and a request has been sent to Dr. Scotto for clarification on which time periods suffered the timing problems. We are awaiting his response, but plans for working around this timing problem can minimize the effects of it on our final analysis, which will be based on daily total irradiances, not hourly or half-hourly irradiances.

A paper on the calibration results, discussed in the previous quarterly report, is being planned. A request for permission to use the RB meter spectral filter response curve data from Dr. Lester Machta has been sent to him. We are still awaiting approval from Dr. Machta to be able to reference this unpublished data in our paper.

Table 1: Description of VISSR data base, containing merged surface irradiance data and GOES VISSR satellite information on an hourly basis.

```
C       Merged VDB & HDB files named VDBTECH.82-85 contain a header record and
C       data records for each hour of the period of the year
C
C       The file is ASCII
C
C
C       Header record contains
C
C       LAT,LON,NYR,ITZONE,SLAT,SLON,THETD,PHID,NDAY1,NDAY2,(IDUMMY(17-44))
C
C
C       NYR = Year
C       ITZONE = Time Zone Number (5=E.S.T.)
C       NDAY1,NDAY2 = First and Last Days for Simulation
C       SLAT = Satellite Latitude (Normally Zero)
C       SLON = Satellite Longitude (Normally -75 Degrees for GOES West)
C       LAT = Target Latitude (Degrees)
C       LON = Target Longitude (Degrees, W = -)
C       THETD = Sat. Zen. Angle at Target (Degrees)
C       PHID = Satellite Azimuth at Target (Degrees)
C
C..............................................................
C
C       Data Records Contain IBUF(1-44) in Integer Format (I5)
C
C       IBUF(1) = Month
C       IBUF(2) = Day of Month
C       IBUF(3) = GMT
C       IBUF(4) = VDB Visible Center Pixel Value (Counts)
C       IBUF(5) = VDB Visible Mean Target Value (Counts * 10)
C       IBUF(6) = VDB Visible Standard Deviation (Counts * 10)
C       IBUF(7) = Precipitable Water from VDB Data (mm * 10)
C       IBUF(8) = VDB IR Center Pixel Value (Counts)
C       IBUF(9) = VDB IR Mean Target Value (Counts * 10)
C       IBUF(10) = VDB IR Standard Deviation (Counts * 10)
C       IBUF(11) = Solar Zen Ang (Watt Formulas, on Half Hour) (Deg * 10)
C       IBUF(12) = Solar Az Ang (Watt Formulas, on Half Hour) (Deg * 10)
C       IBUF(13) = Sun-Satellite Azimuth Angle (Deg*10)
C       IBUF(14) = HDB Upper Level Temperature (Deg * 10)
C       IBUF(15) = HDB Upper Level Dewpoint (Deg * 10)
C       IBUF(16) = Direct Normal (Avg DN & D2) (kJ/m**2)
C       IBUF(17) = Direct Spectral (kJ/m**2)
C       IBUF(18) = Global (Avg of GL & G2) (kJ/m**2)
C       IBUF(19) = Global Speftral (kJ/m**2)
C       IBUF(20) = Diffuse (Tracking Disk) (kJ/m**2)
C       IBUF(21) = Ozone, Dobson Units, from HDB
C       IBUF(22) = Percent Sunshine, from Direct Normal Instrument
C       IBUF(23) = IR from Eppley PIR (kJ/m**2)
C       IBUF(24) = 500nm Turbidity, Base e (%)
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C       IBUF(25) = Solar Zenith Angle, from HDB (Avg over Hour) (Deg*10)
C       IBUF(26) = Precipitable Water from HDB (mm*10)
C       IBUF(27) = Visibility from HDB, km
C       IBUF(28) = Total Cloud Amount, 10ths
C       IBUF(29) = Total Opaque Cloud Amount, 10ths
C       IBUF(30) = Cloud Amount in Layer 1, 10ths
C       IBUF(31) = Cloud Type in Layer 1 (HDB Code)
C       IBUF(32) = Cloud Amount in Layer 2
C       IBUF(33) = Cloud Type in Layer 2
C       IBUF(34) = Cloud Amount in Layer 3
C       IBUF(35) = Global Tilted (kJ/m**2)
C       IBUF(36) = Licor Global Horizontal (kJ/m**2)
C       IBUF(37) = Licor Tilted (kJ/m**2)
C       IBUF(38) = ETR Direct, from HDB (kJ/m**2)
C       IBUF(39) = Horizontal ETR, from HDB (kJ/m**2)
C       IBUF(40) = Min Target Counts by Operational Scheme
C       IBUF(41) = Clear Bi-Directional Reflectance (ERB)
C       IBUF(42) = Cloud Bi-Directional Reflectance (ERB)
C       IBUF(43) = P.CLD Bi-Directional Reflectance (ERB)
C       IBUF(44) = Solar Zen Ang at 6 Minutes after Hour for VISSR Data
C
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SATELLITE TECHNIQUES FOR SURFACE UV RADIATION BUDGET DETERMINATION

C. G. Justus, Principal Investigator

School of Earth and Atmospheric Sciences

Georgia Institute of Technology

April, 1991

QUARTERLY PERFORMANCE REPORT

Report Period: January 1, 1991 - March 31, 1991

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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Under Grant No. NA89AA-D-AC225

Philip A. Arkin, Technical Monitor

Georgia Tech Project G-35-657

The following material was prepared as a portion of the project renewal proposal, recently submitted to NOAA. It outlines the progress to date on the project, discusses the plans for the satellite UV algorithm development, and outlines plans for the remainder of the current project and proposed renewal period.

INTRODUCTION

Measurements of atmospheric ozone by both satellite (Bowman, 1988) and ground-based techniques (Angell, 1988) show that observed recent decreases of total ozone since about 1979 have not been confined to the Antarctic spring season (the Antarctic ozone hole), but are global in extent. There is considerable uncertainty, however, in the potential impact on surface UV radiation exposure which might result from possible continued decreases in stratospheric ozone.

Two recent reports have presented what appears to be conflicting evidence concerning the temporal change of surface UV-B (280-320 nm) irradiance in response to possible long-term stratospheric ozone depletion. Scotto et al. (1988) reported downward trends in UV-B irradiance between 1974 and 1985, as measured at several ground-level monitoring sites across the United States. These authors concluded that "meteorological, climatic, and environmental factors in the troposphere may play a greater role in attenuating UV-B radiation than was previously suspected". Some factors which could possibly explain the results observed by Scotto et al. are: (1) increased reflectance of UV-B, before it reaches the surface, due to an increase in cloud amount, or (2) increased reflection and/or absorption of UV-B by increasing amounts of tropospheric aerosols. Unfortunately, Scotto et al. did not report any observations of trends in cloud fraction or aerosol amount at their measurement sites, nor did they separate their UV-B data into clear-sky and cloudy-sky observations in order to examine these two possible effects.

In contrast to the results of Scotto et al., Blumthaler and Ambach (1990) report an increase in UV-B surface irradiance, at the rate of about 1 percent per year, between 1981 and 1989, as measured at a site in the Swiss Alps. Blumthaler and Ambach restricted their analysis to cloudless days, in order to remove cloud effects on the data. Although these two results appear to contradict one another, there are several possible explanations which would render them consistent: (1) A downward trend in UV-B irradiance throughout the late 70s and early 80s, may have reversed itself in the late 80s; (2) The Alpine measurements, taken above much of the tropospheric aerosols, may indicate a UV-B increase due to decreasing stratospheric ozone, while the U.S. results may indicate that cloud and aerosol effects more than offset this ozone-UV-B response; (3) It is possible that one or the other (or both) sets of observations may suffer from calibration shifts in the instruments during the course of the observation period. Although the instrument used in the Scotto et al. and the Blumthaler and Ambach studies, the Robertson-Berger (RB) meter, has been characterized and calibrated by DeLuisi and Harris (1983), the potential for its drift in calibration over extended (multi-year) observational programs has not been well documented.

This proposal requests renewal of a project, begun just over a year ago under the NOAA Climate and Global Change Program (Justus and Cunnold, 1990). This project has three major goals:

(1) To help clarify which of these possible explanations for the contradictory UV measurement results may most nearly apply, by conducting a measurement study, using data from Atlanta, GA, for the years 1980-1983. This study is using both Robertson-Berger (RB) meter data and data from an Eppley TUVR instrument. Unlike the RB meter, the TUVR instrument responds mostly to the UV-A (320-400 nm) part of the spectrum.

(2) Clarify the role of clouds on surface UV exposure by separate examination of both RB meter and TUVR data under clear-sky and cloudy conditions. The UV fraction of the broad-band surface irradiance is known to increase as clouds diminish the broad-band irradiance (i.e. clouds are relatively more transmissive in the UV than in the full solar spectrum - see Figure 3 of Paris and Justus, 1988).

(3) To develop and test an algorithm for satellite estimation of surface UV exposure. The algorithm should be capable of implementation on a global scale, in quasi-real-time basis, as well as retrospectively on historical data, using ozone and UV reflectance data from TOMS and/or SBUV, and cloud information from ISCCP.

Current algorithms for using satellites to estimate shortwave, broad-band, surface irradiance are accurate to about 5% on a monthly-mean basis, and about 10% on a daily-mean basis (see Figure 6 and Table 1 of Justus et al., 1986). Because of lesser accuracy in ground-truth measuring instruments for UV, and because of strong spectral variations across the UV-B and UV-A bands, a satellite algorithm for estimation of surface UV exposure may be accurate to only about 10-15%. However, this is comparable to the current multi-year stability of UV-A and UV-B instruments (Eppley TUVR, Robertson-Berger meter - see Justus and Cunnold, 1990).

PROJECT RESULTS TO DATE

Table 1 gives values of the observed annual average ratio of RB meter counts to broad-band global surface irradiance in Atlanta for years 1980-1983. Similar annual averages of the TUVR/Global ratio are also given in Table 1. The value of reducing RB data to RB/Global ratio has been demonstrated by Paris and Justus (1988) and Blumthaler and Ambach (1990). The results of Table 1 show that both RB/Global and TUVR/Global ratios increase under the influence of clouds (with the cloudy ratio being about 1.4 times that for the clear ratio). This result is consistent with the earlier results of Paris and Justus and Blumthaler and Ambach.

Table 1 also shows the RB/Global and TUVR/Global ratios, normalized by the four-year average value. These results show that, for clear-sky, and overcast-sky data, as well as for all-sky data, the RB/Global ratio decreased by about 10% over the course of the four years examined. This result is not inconsistent with the downward trend in RB readings reported by Scotto et al. (1988). However, since virtually the same downward trend is seen in clear-sky data as in cloudy data, the results in Table 1 appear to rule out increasing cloud amounts or atmospheric aerosols as a possible cause for this downward trend.

In Table 1, the TUVR/Global ratios, normalized by the four-year average value of this ratio, increase by about 10% over the course of the four years studied. This increase, of course, cannot be explained by an increase in cloud fraction or aerosols during the years of the study. Model studies (Justus and Cunnold, 1990) verify that the TUVR response to ozone change is very small, so the observed increase in TUVR readings cannot be attributed to a decrease in ozone amount. The fact that these respective decreases (in RB/Global) and increases (in TUVR/Global) are similar for clear-sky, cloudy-sky and all-sky observations, indicates that both temporal trends are due to calibration drift of the respective instruments (i.e. about 2.5% per year drift, downward for the RB meter and upward for the TUVR).

These results indicate that the observed downward trends in UV-B reported by Scotto et al. (1988) may be due to calibration shifts in the RB meters used. The upward trends in UV-B irradiance reported by Blumthaler and Ambach (1990) are also rendered suspect due to the possibility of a calibration shift in the opposite direction (as seen in the TUVR results here). Therefore, until instruments are developed and employed for which calibrations can be maintained better than the RB meter and TUVR, trends of UV-B and UV-A irradiance of the order of 1-2% per year cannot be attributed to changes in stratospheric ozone in an unambiguous fashion.

In order to better understand the response of the RB meter and TUVR to the effects of solar zenith angle, ozone, aerosols and clouds, and to serve as the basis for the proposed method for determining surface UV irradiance from satellite observations, a spectral radiative transfer model (Justus and Cunnold, 1990) has been adapted for use in simulating the response of the RB meter and TUVR. This model, a variant of the delta-Eddington model described by Paris and Justus (1988), has been modified to work at 1 nm spectral resolution, and to utilize ozone absorption coefficients determined from averaging the data of Bass and Paur (1985; also Paur and Bass, 1985), Molina and Molina (1986) and Cacciani et al. (1989). The model uses spectral filter factors for the RB meter and TUVR, and integrates across the respective spectral intervals of the instruments, in 1 nm spectral steps.

Good results have been obtained thus far (Justus and Cunnold, 1990) between the model values and observed clear-sky values of RB meter and TUVR readings, under a variety of ozone, solar angle, aerosol and seasonal variations. Comparison between the model and observations under cloudy conditions is continuing.

SATELLITE ALGORITHMS FOR MEASURING THE SURFACE UV RADIATION BUDGET

Algorithms for satellite-determination of the shortwave (UV to near-IR) radiation budget at the surface must rely on models to compute the atmospheric absorption. If, at wavelength λ, the planetary reflectance is $r_{p\lambda}$, then from the known extraterrestrial spectral irradiance, $E_{o\lambda}$, the absorptance of the Earth-atmosphere system, $a_{p\lambda}$, can be determined by satellite-measured reflected irradiance, $E_{r\lambda}$. That is,

$$a_{p\lambda} = 1 - r_{p\lambda} = (E_{o\lambda} - E_{r\lambda})/E_{o\lambda} \quad . \tag{1}$$

In order to determine the surface irradiance, $E_{s\lambda}$, the transmittance or absorptance through the atmosphere must be known. Simple energy balance (Kirchoff's law) shows that

$$E_{s\lambda} = E_{o\lambda} (a_{p\lambda} - a_{a\lambda}) / (1 - r_{s\lambda}) \quad , \tag{2}$$

where $a_{a\lambda}$ is the atmospheric absorptance and $r_{s\lambda}$ is the surface reflectance. Therefore, an algorithm to determine $E_{s\lambda}$ by satellite measurements will take the following general form:

[1] Determine the surface reflectance by satellite-measurements under clear sky conditions (when $E_{s\lambda}$ and $a_{a\lambda}$ can be accurately modeled), and solve equation (2) for $r_{s\lambda}$

[2] Under general (cloudy or partly cloudy) conditions, determine the planetary absorptance $a_{p\lambda}$ from the satellite-measured reflected irradiance by equation (1)

[3] Under general conditions, use a radiative transfer model to calculate $a_{a\lambda}$, and use this with $r_{s\lambda}$ (determined in step [1]) and $a_{p\lambda}$ (measured in step [2]) to evaluate $E_{s\lambda}$ by equation (2)

For the computations of atmospheric absorptance $a_{a\lambda}$, for steps [1] and [3], an accurate (but time-consuming) model such as the Discrete-Ordinate-Method of Stamnes et al. (1988) may be used for algorithm development. For operational implementation, however, a more rapid (but reasonably accurate) model such as the delta-Eddington method of Paris and Justus (1988) must be used.

A slight variation on equation (2) is frequently used in insolation algorithms for broad-band, shortwave irradiance at the surface (Justus et al., 1986) and would be similarly appropriate for use in satellite estimates of UV surface irradiance. This technique utilizes the fact that equation (2) is linear in the planetary albedo, r_p, and defines a "radiatively effective cloud fraction", C_e, by the relationship

$$r_p = r_{clr} + C_e (r_{cld} - r_{clr}) \quad , \tag{3}$$

where r_{clr} is r_p under cloud-free conditions (e.g. minimum planetary albedo over some time period at the target site), and r_{cld} is r_p under very thick, overcast cloud conditions (e.g. maximum planetary albedo over some time period at the same target site).

Note that the radiatively effective cloud fraction, C_e, is distinctly different from conventional cloud fraction values, such as that reported by surface-based observers, or measured by vertically pointing lidars or ceilometers. By definition, C_e appears linearly in equation (3), but the corresponding relationship for r_p would have non-linear dependence on any of these conventional measures of cloud fraction.

Radiative transfer models [such as the Stamnes et al. (1988) or Paris and Justus (1988) models] can be used to compute clear-sky and overcast-sky surface irradiances (E_{clr} and E_{cld}, respectively), corresponding to the satellite-observed values of r_{clr} and r_{cld}. The same radiatively-effective cloud fraction is then assumed to apply to surface irradiance. Namely, it is assumed that

$$
\begin{aligned}
E_s &= E_{clr} + C_e (E_{cld} - E_{clr}) \\
&= E_{clr} + (r_p - r_{clr}) [(E_{cld} - E_{clr})/(r_{cld} - r_{clr})] \quad , \qquad (4)
\end{aligned}
$$

where the last step in (4) makes use of a solution of C_e from equation (3).

In the approach of equation (4), E_s is assumed to depart from its clear-sky value, E_{clr}, by an amount which is proportional to the contrast between the observed planetary albedo and minimum (clear-sky) planetary albedo. That is, the last term in (4) is proportional to $(r_p - r_{clr})$ by the quantity in square brackets in that term. Thus

$$E_s = E_{clr} + F (r_p - r_{clr}) \quad , \qquad (5)$$

where the proportionality factor F depends on the quantities E_{clr} and E_{cld}, which are derived from the radiative transfer model, based on the pre-determined clear-sky and overcast-cloud planetary albedo values r_{clr} and r_{cld}. A satellite algorithm for surface UV irradiance, based on equation (5), would thus involve steps in its evaluation, which are only slightly different from the steps [1] - [3], described above, for an algorithm based on equation (2).

An actual satellite algorithm does not necessarily have to work with precisely the same wavelength (or wavelength band) as that for which the surface irradiance is desired. Thus, broad-band surface irradiance may be estimated from satellite measurements in the GOES visible band (Justus et al., 1986). Or, in the inverse process to steps [1]-[3], surface-measured, broad-band irradiance may be used to compute top-of-atmosphere, filter-band, reflected radiance for purposes of calibrating GOES visible-band sensors (Paris and Justus, 1988) or AVHRR visible or near-IR sensors (Justus, 1988).

For determination of the UV planetary reflectance (for steps [1] and [2] above), reflectances measured by TOMS or SBUV can be used (Eck et al., 1987; Frederick, 1987). At UV wavelengths, the atmospheric absorptance depends strongly on ozone, but ozone column amount and profile can be measured by satellite (Frederick and Serafino, 1985; Reinsel et al., 1988).

In addition to a dependence on total ozone column amount, the atmospheric absorptance also depends on the ozone profile. Tropospheric ozone exerts a disproportionate influence on absorption (Bruhl and Crutzen, 1989). In the troposphere, ozone mixture with scatterers enhances the absorption capability of each ozone molecule over that of a stratospheric ozone molecule, which is in a relatively non-scattering environment. Currently tropospheric ozone makes up about 10% of the total column amount, but the results of Bruhl and Crutzen indicate that it may contribute about 30% of the total ozone absorption. The average concentration of ozone in the troposphere may be increasing at the rate of about 1% per year (Dutsch and Staehelin, 1989). Satellite information from SAGE, or from a difference between SAGE and SBUV, can be used to estimate the tropospheric ozone amount (Fishman et al., 1986, Fishman, 1988), and this effect can thus be accounted for.

Clouds exert a strong influence on the UV surface irradiance (Paris and Justus, 1988; Frederick and Lubin, 1988; Blumthaler and Ambach, 1990; Frederick, 1990). Unfortunately TOMS and SBUV do not have good spatial resolution for determining cloud field properties (cloud fraction, cloud albedo, etc.). However, the algorithm under development for this project will use higher resolution sensors, such as GOES or AVHRR, to determine the cloud characteristics. The proposed algorithm would thus use SBUV (or TOMS) to determine ozone amount and planetary reflectance in steps [1]-[3] above, but computed atmospheric absorptance would rely on the cloud-field estimates from the higher resolution GOES (or AVHRR) sensors. For retrospective studies, the ISCCP (level C) cloud data, compiled from 4-8 km resolution satellite data, could be used to provide global surface UV exposure estimates to a spatial resolution as high as 250 × 250 km.

The potential list of parameters which might appear in the final algorithm is large, and some of these parameters have fairly strong spectral variation. At stratospheric heights, this potential list includes: ozone column amount and vertical profile, stratospheric aerosol optical depth, single-scatter albedo, and asymmetry parameter. For the cloud-free troposphere, potentially important parameters include the Rayleigh optical depth, tropospheric aerosol optical depth, single-scatter albedo, and asymmetry parameter. For the partly-cloudy or overcast-cloud tropospheric case, we must add to this list the normal cloud fraction, the cloud optical depth, single-scatter albedo, and asymmetry parameter, and cloud height(s), cloud layer thicknes(es) (for overcast cases), and cloud thickness/width ratio(s) (for partial cloud cases).

At all height levels, there is dependence on the solar zenith angle, and, for the interpretation of satellite-measured radiances into terms of upwelling irradiance, the top-of-atmosphere bidirectional-reflectance-factor is important (see, for example, Justus and Paris, 1985; Eck et. al., 1987).

The radiative transfer models of Stamnes et al. (1988) and Paris and Justus (1988) can be used to study the sensitivity of surface UV irradiance to most of these parameters. The Paris and Justus model is designed to treat three vertical layers, with spectral resolution of 1 nm in the UV (Justus and Cunnold, 1990). The Stamnes et al. model can treat a large number of vertical layers, but is well set up for treatment of only one monochromatic wavelength at a time. Although both of these models can treat the clear-sky and overcast-cloud-layer cases, neither can treat the case of a partial cloud field.

A model developed recently by a former Ph.D. student of Dr. Justus (Luo, 1990) is designed to treat partial cloud layers. Luo successfully compared results of his model with results from much more time consuming models, such as Monte Carlo techniques. The Luo model for partial cloud effects is especially well suited for computing the non-linear relationship which exists between the radiatively effective cloud fraction [C_e of equations (3) and (4)] and conventional cloud fraction measurements (such as normal cloud fraction or surface-observer-reported cloud fraction).

One of the first tasks will be to conduct sensitivity studies, using the models of Paris and Justus (1988), Stamnes et al. (1988) and Luo (1990). This sensitivity analysis will determine which of the above list of possibly important model parameters must be retained in the final, simplified algorithm for UV surface irradiance. These model tests will also determine whether the simple modeling approach of equation (5) is adequate, or whether the approach of equation (2) is better. The analysis will also study whether a simple two-layer model, based of radiative transfer through the stratosphere to cloud-top-level, with a Luo-type cloud layer below, is the best approach for treating the non-linearities of partial cloud fields.

An important sensitivity test to be conducted with these models will be to determine whether it is important or not to separate out the effects of tropospheric ozone, and therefore whether the SAGE-SBUV analysis, discussed above, will be a required part of the final algorithm, or whether climatological values for tropospheric ozone may be assumed. It will also be important to use these sensitivity studies to determine to what extent the height profile of the stratospheric ozone must be specified, or whether the algorithm can be accurately based on just the total ozone column amount. This will determine whether the final algorithm can be based on TOMS total ozone or if SBUV-measured ozone profiles must be used.

REFERENCES

Angell, J. K. (1988): An Update through 1985 of the Variations in Global Total Ozone and North Temperate Layer-Mean Ozone, J. Appl. Meteorol., 27: 91-97.

Bass, A.M. and R.J. Paur (1985): "The Ultraviolet Cross-Section of Ozone: I. The Measurements", Proceedings of the Quadrennial Ozone Symposium, Halkidiki, Greece, 3-7 September 1984, C.S. Zerefos and A. Ghazi, eds., 606-610.

Blumthaler, M., and W. Ambach (1990): "Indication of Increasing Solar Ultraviolet-B Radiation Flux in Alpine Regions", Science, 248, 206-208.

Bruhl, C. and P. J. Crutzen (1989): On the Disproportionate Role of Tropospheric Ozone as a Filter Against Solar UV-B Radiation, Geophys. Res. Lett., 16(7), 703-706.

Cacciani, M. et al. (1989): "Absolute Determination of the Cross Sections of Ozone in the Wavelength Region 339-355 nm at Temperatures 220-293 K", J. Geophys. Res., 94(D6): 8485-8490.

DeLuisi, J.J. and J.M. Harris (1983): "A Determination of the Absolute Radiant Energy of a Robertson-Berger Meter Sunburn Unit", Atmos. Environ., 17(4): 751-758.

Dutsch, H.U. and J. Staehelin (1989): "How Much Information on Anthropogenic Influences on the Ozone Layer can be Obtained from a Set of One-Station Observations?", in Ozone in the Atmosphere, Proc. Quadrennial Ozone Symposium 1988 and Tropospheric Ozone Workshop, R.D. Bajkov and P. Fabian eds., A. Deepak Pub. Co., Hampton, VA., 822 pp.

Eck, T. F., et al. (1987): Reflectivity of Earth's Surface and Clouds in Ultraviolet from Satellite Observations, J. Geophys. Res., 92(D4), 4287-4296.

Fishman, J. et al. (1986): The Use of Satellite Data to Study Tropospheric Ozone in the Tropics, J. Geophys. Res., 91, 14451-14465.

Fishman, J. (1988): Tropospheric Ozone from Satellite Total Ozone Measurements, Tropospheric Ozone, D. Reidel Pub. Co., 111-123.

Frederick, J. E. (1987): The Ultraviolet Spectral Albedo of Planet Earth, Tellus, 39B(3), 261-270.

Frederick, J. E. (1990): Tropospheric Influence on Solar Ultraviolet Radiation: The Role of Clouds, J. Clim., 3(3), 373-381.

Frederick, J. E. and D. Lubin (1988): The Budget of Biologically Active Ultraviolet Radiation in the Earth-Atmosphere System, J. Geophys. Res., 93(D4), 3825-3832.

Frederick, J. E. and G. N. Serafino (1985): The Detection of Long-Term Changes in Stratospheric Ozone: Scientific Requirements and Current Results from Satellite-Based Measurement Systems, J. Clim. Appl. Meteorol., 24(9), 904-914.

Justus, C. G. (1988): Calibration of Satellite Shortwave Sensors Using Overcast Cloud Layer Targets, Proc. SPIE, 924, 120-128.

Justus, C. G. and D. M. Cunnold (1990): Satellite Techniques for Surface UV Radiation Budget Determination, NOAA Climate and Global Change Grant No. NA89AA-D-AC225, quarterly reports, January, April, July, October.

Justus, C. G. and M. V. Paris (1985): A Model for Solar Spectral Irradiance and Radiance at the Bottom and Top of a Cloudless Atmosphere, J. Clim. Appl. Meteorol., 24, 193-205.

Justus, C. G. et al. (1986): Satellite-Measured Insolation in the United States, Mexico, and South America, Remote Sens. Environ., 20, 57-83.

Luo, Gang (1990): A Cloud Fraction and Radiative Transfer Model, Ph.D. thesis, School of Earth and Atmospheric Sciences, Georgia Institute of Technology, 144pp.

Molina, L.T. and M.J. Molina (1986): "Absolute Absorption Cross Sections of Ozone in the 185- to 350-nm Wavelength Range", J. Geophys. Res., 91(D13): 14,501-14,508.

Paris, M. V. and C. G. Justus (1988): A Cloudy-Sky Radiative Transfer Model Suitable for Calibration of SAtellite Sensors, Remote Sens. Environ., 24(2), 269-285.

Paur, R.J. and A.M. Bass (1985): "The Ultraviolet Cross-Sections of Ozone: II. Results and Temperature Dependence", Proceedings of the Quadrennial Ozone Symposium, Halkidiki, Greece, 3-7 September, 1984, C.S. Zerefos and A.Ghazi, eds., 611-616.

Reinsel, G. C. et al. (1988): An Analysis of the 7-year Record of SBUV Satellite Ozone Data: Global Profile Features and Trends in Total Ozone, J. Geophys. Res., 93(D2), 1689-1703.

Scotto, J., et al. (1988): Biologically Effective Ultraviolet Radiation: Surface Measurements in the United States, 1974 to 1985. Science, 239: 762-764

Stamnes, K., S. C. Tsay, W. Wiscombe and K. Jayaweera (1988): Numerically Stable Algorithm for Discrete-Ordinate-Method Radiative Transfer in Multiple Scattering and Emitting Layered Media, Appl. Optics, 27(12), 2502-2509.

Table 1. Ratios (RB meter/Global) and (TUVR/Global), and ratios normalized by their 4-year mean value, with data separated into cloudy, clear and all-sky conditions. Observations were taken in Atlanta, GA.

	RB/Global, counts $kJ^{-1}m^2$			TUVR/Global, unitless		
Year	Cloudy	All-Sky	Clear	Cloudy	All-Sky	Clear
1980	0.2924	0.2692	0.2161	0.0646	0.0487	0.0460
1981	0.3022	0.2729	0.2213	0.0648	0.0497	0.0466
1982	0.2786	0.2572	0.2034	0.0732	0.0547	0.0507
1983	0.2687	0.2520	0.1926	0.0703	0.0549	0.0516
AVG	0.2855	0.2628	0.2084	0.0682	0.0520	0.0487

	RB/Global, Rel. to 4-yr Mean			TUVR/Global, Rel. to 4-yr Mean		
Year	Cloudy	All-Sky	Clear	Cloudy	All-Sky	Clear
1980	1.024	1.024	1.037	0.947	0.937	0.944
1981	1.058	1.038	1.062	0.950	0.956	0.956
1982	0.976	0.979	0.976	1.073	1.052	1.041
1983	0.941	0.959	0.924	1.031	1.056	1.059
AVG	1.000	1.000	1.000	1.000	1.000	1.000

G-35-657

SATELLITE TECHNIQUES FOR SURFACE UV RADIATION BUDGET DETERMINATION

C. G. Justus, Principal Investigator

School of Earth and Atmospheric Sciences

Georgia Institute of Technology

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Philip A. Arkin, Technical Monitor

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PROGRESS TO DATE

The last quarterly report gave an overview of progress up to the previous quarter. During the previous quarter, work has concentrated on the conversion of programs and data bases to the new IBM RS/6000 workstation system.

All of the spectral radiative transfer model programs and data bases have now been set up on the RS/6000 system. Chief among the spectral programs is SPECLD, which can do radiative transfer calculations for clear-sky or overcast-cloud cases in the UV wavelength (0.25-0.40 μm) at 0.001 μm resolution.

Data bases and reading/analysis programs to work with our multi-year radiation and GOES satellite data have also been set up on the RS/6000. These data include the UV-A data measured with the Eppley TUVR at Georgia Tech. These data, together with the UV-B data from Atlanta measurements with an RB-meter, will serve as validation data sets for the algorithms to be developed.

PLANS FOR THE COMING PERIOD

Specific model and data studies will begin which will lead toward the UV-A and UV-B satellite algorithms. Work on extracting ozone and top-of-atmosphere UV radiances for SAGE/SBUV data sets will also begin.

SATELLITE TECHNIQUES FOR SURFACE UV RADIATION BUDGET DETERMINATION

C. G. Justus, Principal Investigator

School of Earth and Atmospheric Sciences

Georgia Institute of Technology

Atlanta, GA 30332

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Abstract

A study of UV-B and UV-A irradiance measurements in Atlanta, from 1980-84 indicates that, while Robertson-Berger (RB) meter readings are trending downward by about 10% over the study period, Eppley TUVR readings are trending upward at about the same rate. Similar trends are seen in annual mean values and in summer and winter seasonal values. The most consistent interpretation of these results is that the trends are not due to changes in ozone, cloud-cover or aerosol effects, but due to drifts in the calibration of both of the instruments. The Paris and Justus (1988) spectral radiative transfer model has been used to assess the calibration of the RB-meter and TUVR instruments and to develop a simple algorithm which can be used to estimate the UV-A (RB-meter) or UV-B (TUVR) irradiance at the surface, from satellite measurements of ozone and reflectance. Preliminary algorithms are presented, which will be further tested against the ground-based and satellite-measured data that have been collected.

PROGRESS DURING THE PROJECT PERIOD

UV Measurement Study Results

Two recent reports have presented what appears to be conflicting evidence concerning the temporal change of surface UV-B (280-320 nm) irradiance in response to possible long-term stratospheric ozone depletion. Scotto et al. (1988) reported downward trends in UV-B irradiance between 1974 and 1985, as measured at several ground-level monitoring sites across the United States. These authors concluded that "meteorological, climatic, and environmental factors in the troposphere may play a greater role in attenuating UV-B radiation than was previously suspected". Some factors which could possibly explain the results observed by Scotto et al. are: (1) increased reflectance of UV-B, before it reaches the surface, due to an increase in cloud amount, or (2) increased reflection and/or absorption of UV-B by increasing amounts of tropospheric aerosols. Unfortunately, Scotto et al. did not report any observations of trends in cloud fraction or aerosol amount at their measurement sites, nor did they separate their UV-B data into clear-sky and cloudy-sky observations in order to examine these two possible effects.

In contrast to the results of Scotto et al., Blumthaler and Ambach (1990) report an increase in UV-B surface irradiance, at the rate of about 1 percent per year, between 1981 and 1989, as measured at a site in the Swiss Alps. Blumthaler and Ambach restricted their analysis to cloudless days, in order to remove cloud effects on the data. Although these two results appear to contradict one another, there are several possible explanations which would render them consistent: (1) A downward trend in UV-B irradiance throughout the late 70s and early 80s, may have reversed itself in the late 80s; (2) The Alpine measurements, taken above much of the tropospheric aerosols, may indicate a UV-B increase due to decreasing stratospheric ozone, while the U.S. results may indicate that cloud and aerosol effects more than offset this ozone-UV-B response; (3) It is possible that one or the other (or both) sets of observations may suffer from calibration shifts in the instruments during the course of the observation period. Although the instrument used in the Scotto et al. and the Blumthaler and Ambach studies, the Robertson-Berger meter, has been characterized and calibrated by DeLuisi and Harris (1983), the potential for its drift in calibration over extended (multi-year) observational programs has not been well documented.

A measurement study has been done, using data from Atlanta, GA, for the years 1980-1983, to help clarify which of these possible explanations may most nearly apply. This study used both Robertson-Berger (RB) meter data and data from an Eppley TUVR instrument. Unlike the RB meter, the TUVR instrument responds mostly to the UV-A (320-400 nm) part of the spectrum. Relative filter factors for the RB meter and the TUVR are shown in Figure 1. The RB filter information was taken from Machta and Hass (1978), and the TUVR filter data were obtained with the instrument, from the Eppley Laboratory, Inc. The RB meter was operated in Atlanta, as part of the same National Cancer Institute network, reported on by Scotto et al. (1988). The TUVR was operated on the Atlanta campus of the Georgia Institute of Technology, as part of the Department of Energy-sponsored Solar Energy Meteorological Research and Training Site (SEMRTS) program (Paris and Justus, 1988).

Figure 2 shows results for monthly-average daily total irradiance from the RB meter (in RB counts) and the TUVR (in kJ/m^2). The TUVR irradiances are expressed in kJ/m^2, with the use of a calibration factor obtained from the Eppley Laboratory, as adjusted by comparison of the Atlanta TUVR against a travelling standard TUVR, operated under the SEMRTS program. RB irradiances are sometimes expressed in "sunburn units" (SU), with 440 counts = 1 SU. Absolute energy flux per SU has been determined for the RB meter, by DeLuisi and Harris (1983), to be a non-linear function of solar zenith angle and total column ozone amount.

The data of Figure 2 show that RB irradiance increases non-linearly as the TUVR irradiance increases. The monthly-average daily total irradiances of this Figure both vary primarily with the seasonal changes in monthly average solar zenith angle. The non-linear relationship exhibited by Figure 2, is therefore an indication that the RB meter and the TUVR respond differently to changes in solar zenith angle. This conclusion is borne out by model studies, reported in the next section of this report.

When the data of Figure 2 are separated by year, it is seen that the RB/TUVR ratio is approximately 20% larger for years 1980-81 than for years 1982-83. Data in Tables 1-3 present evidence to explain this temporal trend in RB/TUVR ratio.

Table 1 presents data on the average, daily-total, broadband (0.3 - 4 μm) irradiance, as measured at the SEMRTS station in Atlanta, with data separated according to days which were clear or overcast, as well as days under all cloud conditions. Only days with complete measurements of all three irradiance components (global, RB meter and TUVR) were considered. Table 1 also shows, by year, the total number of days analyzed in the cloudy, clear and all-sky categories, along with the annual-average sunshine duration for each year, as measured by an automatic sunshine duration recorder (Paris and Justus, 1988). The hourly sunshine duration readings for each day were used in the separation of the data into clear-day and overcast-day subsets.

Table 2 shows average daily total irradiances from the RB meter (counts) and the TUVR (kJ/m^2), by year, for the same data set as in Table 1. Data from Tables 1 and 2 are used to produce values for the ratios RB/Global and TUVR/Global. The value of reducing RB data to RB/Global ratio has been demonstrated by Paris and Justus (1988) and Blumthaler and Ambach (1990). The results of Table 3 show that both RB/Global and TUVR/Global ratios increase under the influence of clouds. This result is consistent with the earlier results of Paris and Justus and Blumthaler and Ambach.

Figure 3 presents the RB/Global ratios of Table 3, normalized by the four-year average value of this ratio (also shown in Table 3). This Figure shows that, for clear-sky, and overcast-sky data, as well as for all-sky data, the RB/Global ratio decreased by about 10% over the course of the four years examined. This result is not inconsistent with the downward trend in RB readings reported by Scotto et al. (1988). However, since virtually the same downward trend is seen in clear-sky data as in cloudy data, the results in Figure 3 appear to rule out increasing atmospheric aerosols as a possible cause for this downward trend. Based on Table 1, the years 1982-83 had larger average cloud fraction (smaller sunshine duration) than did the years 1980-81. Therefore the effects of increasing cloud fraction to cause the downward trend in Figure 3 cannot yet be ruled out.

A similar plot of TUVR/Global ratio, normalized by the four-year average value of this ratio, is shown in Figure 4. In contrast to the RB/Global ratio, the TUVR/Global ratio increases by about 10% over the course of the four years studied. This increase, of course, cannot be explained by the observed increase in cloud fraction during the later years of the study. Model studies (presented in the next section) verify that the TUVR response to ozone changes is very small, so the observed increase in TUVR readings cannot be attributed to decreases in ozone amount. Therefore, the observed decrease in RB/TUVR ratio by about 20%, shown in Figure 2, is due to a decrease of about 10% in measured RB irradiance, accompanied by about a 10% increase in measured TUVR irradiance. The fact that these respective decreases and increases are similar for clear-sky, cloudy-sky and all-sky observations, indicates that both temporal trends are due to calibration drift of the respective instruments (i.e. about 2.5% per year drift, downward for the RB meter and upward for the TUVR).

Recently, Liu et al. (1991) have pointed out that, since stratospheric ozone has a large seasonal variation at mid latitudes (with a summer minimum), that it might be possible to distinguish the effects of ozone from the effects of aerosols on the UV-B irradiance at the surface. Figures 5 and 6 show values of the temporal trends in the seasonally-averaged ratios of RB-meter/Global and TUVR/Global for the study period. Considering the amount of uncertainty in the data, both winter (December-January-February) and summer (June-July-August) values show about the same rate of downward trend in RB/Global values for the seasonal data (Figure 5) as for the annual mean data (Figure 3). For the TUVR/Global ratio, the upward trend over the study period is also about the same for the seasonal data (Figure 6) as for the annual mean data (Figure 4).

All of these results indicate that the observed downward trends in UV-B reported by Scotto et al. (1988) may be due to calibration shifts in the RB meters used. The upward trends in UV-B irradiance reported by Blumthaler and Ambach (1990) are also rendered suspect due to the possibility of a calibration shift in the opposite direction (as seen in the TUVR results here). Therefore, until instruments are developed and employed for which calibrations can be maintained better than the RB meter and TUVR, trends of UV-B and UV-A irradiance of the order of 1-2% per year cannot be attributed to changes in stratospheric ozone in an unambiguous fashion.

UV Modeling Study Results

In order to better understand the response of the RB meter and TUVR to the effects of solar zenith angle, ozone, aerosols and clouds, and to serve as the basis for the proposed method for determining surface UV irradiance from satellite observations, a spectral radiative transfer model has been adapted for use in simulating the response of the RB meter and TUVR. This model, a variant of the delta-Eddington model described by Paris and Justus (1988), has been modified to work at 1 nm spectral resolution, and to utilize ozone absorption coefficients determined from averaging the data of Bass and Paur (1985; also Paur and Bass, 1985), Molina and Molina (1986) and Cacciani et al. (1989). The model uses spectral filter factors for the RB meter and TUVR as given in Figure 1, and integrates across the respective spectral intervals of the instruments, in 1 nm spectral steps.

To calibrate the model versus the observations, a set of 18 clear days in March, May and December, 1981 were analyzed and modeled. The hourly and daily data in this selected set span a wide range of solar zenith angles (daily averages 14° to 57°), ozone column amounts (0.28 cm to 0.44 cm) and aerosol optical depths (0.12 to 0.29). The measured TUVR irradiances were found to be linearly related to the modeled TUVR irradiances, with the relation

$$\mathrm{TUVR(measured)} = 1.575\ \mathrm{TUVR(modeled)} \quad . \tag{1}$$

Because of uncertainties in the absolute transmittance of the TUVR filter, and other instrument calibration uncertainties, the fact that the coefficient in this relationship differs significantly from 1 is not considered significant.

For the RB meter, a non-linear calibration relating the modeled values to observed values was found, given by

$$R = 95.93\ M + 15.141\ M^2 \quad , \tag{2}$$

where R is the measured hourly RB meter irradiance (in counts) and M is the modeled hourly RB meter irradiance in J/m^2. Although this calibration is non-linear, the average energy flux per sunburn unit over the range of measured values in the calibration data set is about 2.6 $J\ m^{-2}$ / SU (26 $mJ\ cm^{-2}$ / SU), a value not inconsistent with results observed for the RB meter by DeLuisi and Harris (1983).

Using the calibrations of equations (1) and (2), Figures 7 and 8 show comparisons between measured and modeled hourly RB meter and TUVR irradiance versus time of day for May 2 and December 20, 1981. The agreement between measured and modeled values demonstrated by these two Figures is considered to be satisfactory. Comparison of Figures 7 and 8 shows that, as the time of day changes, the RB meter irradiances drop more quickly with increasing solar zenith angle than is the case with the TUVR irradiances. This result explains the non-linear relationship between RB meter and TUVR irradiances seen in Figure 2. That is, as monthly average solar zenith angles increase from summer to winter, the RB meter values drop at a faster rate than do the TUVR irradiances.

To examine the modeled and measured sensitivity to ozone changes, a sequence of clear-sky data in December 1981 (during which the ozone column amount ranged from about 0.28 cm to about 0.44 cm) was examined. Figure 9 shows results for the measured and modeled RB meter irradiances at the solar noon hour on these days. The solid line in Figure 9 is the observed ozone sensitivity of the RB meter, as determined by DeLuisi and Harris (1983) [a 1.24 percent change in RB meter irradiance for every 1% change in ozone column amount].

Results in Figure 10 demonstrate that the ozone sensitivity for the TUVR measured and modeled values is very small, but with decreasing irradiance for increasing ozone amount. Figure 10 shows values for the measured and modeled daily total TUVR irradiance, with the line indicating a quadratic best fit to the model results. Again, the agreement between the measured and model results is considered to be satisfactory.

Measured and modeled daily total irradiances for all 18 clear days used in the calibration study are shown in Figures 11 (RB meter) and 12 (TUVR). These figures show that, with the model calibrations given in equations 1 and 2, the measured and modeled values follow closely the one-to-one lines for both the RB meter and TUVR results. Thus, for clear-sky conditions, the spectral model has been demonstrated to account adequately for changes in solar zenith angle, ozone amount and aerosol amount.

Development and Testing of the Satellite-UV Irradiance Algorithms

The major goal of this project is to develop an algorithm that can be used to convert satellite-measured values of ozone amount and reflectance to an estimate of UV-A and UV-B irradiance at the surface. The approach to be used is similar to that of Justus et al. (1986) for the computation of broad-band solar irradiance at the surface, from satellite-measured reflectance. In this approach, the satellite-measured reflectance is used as a measure of the cloud influence on the surface irradiance.

For the UV-A and UV-B algorithms, the spectral model of Paris and Justus (1988) will be used to determine the sensitivities of the UV surface irradiance to ozone, solar zenith angle and cloud cover. From a large set of spectral model runs for various solar zenith angles, ozone column amounts, and cloud optical depth values, a simple algorithm expression for the UV transmittance, of the form

$$T = T_o (1 - a R - b R^2) \tag{3}$$

has been found to adequately represent the spectral model results. In equation (3), T_o is the clear-sky UV transmittance, as a function of ozone column amount and solar zenith angle, R is the normalized filter-band reflectance measured by the satellite, defined by

$$R = (R_m - R_o) / (R_c - R_o) \quad , \tag{4}$$

and a and b are empirical coefficients, determined by fitting the spectral model results. The parameter R_o in equation (4) is the clear-sky reflectance of the satellite target area (dependent on the target area albedo), and R_c is the overcast-cloud reflectance for a cloud layer of infinite optical depth (as determined by the spectral model simulations).

The Fortran source code for the initial algorithms to be tested is given in the Appendix. The function rbflux computes the surface downwelling RB-meter filter-band irradiance (in W m^{-2} μm^{-1}), from the solar zenith angle, the GOES visible-band reflectance, the clear-sky GOES visible-band reflectance, the total ozone column amount (in atm. cm), and the RB-meter filter-band extra-terrestrial solar irradiance on a horizontal surface (in W m^{-2} μm^{-1}). The function tuvrflux performs a similar process for the surface downwelling Eppley TUVR filter-band irradiance. Comparisons are shown in Figures 13 and 14 of results from the simple regression model algorithms [i.e. equation (3)], with a large set of results from the complete spectral model, under a variety of ozone, solar zenith angle, and reflectance conditions. Figure 13 shows that the algorithm (rbflux) reproduces the spectral model results to within an accuracy of 7.1% (as measured by the coefficient of variation) and that the tuvrflux algorithm reproduces the spectral model results with an accuracy of 4.2%.

PLANS FOR THE COMING PROJECT PERIOD

This project has been recently extended (under a different grant number). Plans for this extended period are to test the rbflux and tuvrflux algorithms against actual measurements made at the surface by RB-meter and TUVR instruments and from a GOES satellite. The Atlanta (Georgia Tech) data discussed above will be used in this algorithm validation study.

A problem which had been noted in the RB-meter measurement data was that the timing information seemed to be off by a varying amount from that reported. In order to conduct the algorithm validation, it is necessary to have RB-meter values measured for the same time period as the corresponding satellite-measured reflectances. To correct this timing problem, a method has been developed which computes the cross-correlation between each days values of the Eppley TUVR readings with the RB-meter readings for the same day. The time shift in the RB-meter data that would be necessary to maximize this cross correlation is taken to be the temporal offset of the RB-meter data from their reported values for that day. Figure 15 shows results for the daily time shift values computed by this procedure, for the 1980-84 period of the Atlanta (Georgia Tech) data. The RB-meter time shifts are seen to average about -1/2 hour, but with variations in the time shift ranging from about 0 to -1 hour.

The VISSR-band reflectance measured by GOES will be used to determine the cloud effects in the algorithm validation study. The ozone column amounts will be those determined by the TOMS or SBUV satellite instruments when viewing the Atlanta (Georgia Tech) target area. A set of TOMS and SBUV data have already been obtained for use in this algorithm validation study for the 1980-84 time period.

Acknowledgments

Sincere thanks are expressed to Dr. Joseph Scotto, of the National Cancer Institute, for supplying the Robertson-Berger meter data for Atlanta, to Dr. James E. Norris, of the National Institute of Standards and Technology, for supplying the Bass and Paur ozone absorption coefficient data, and to Dr. John DeLuisi, for helpful discussion and correspondence concerning the characterization of the Robertson-Berger meter.

REFERENCES

Bass, A.M. and R.J. Paur (1985): "The Ultraviolet Cross-Section of Ozone: I. The Measurements", Proceedings of the Quadrennial Ozone Symposium, Halkidiki, Greece, 3-7 September 1984, C.S. Zerefos and A. Ghazi, eds., 606-610.

Blumthaler, M., and W. Ambach (1990): "Indication of Increasing Solar Ultraviolet-B Radiation Flux in Alpine Regions", Science, 248, 206-208.

Cacciani, M. et al. (1989): "Absolute Determination of the Cross Sections of Ozone in the Wavelength Region 339-355 nm at Temperatures 220-293 K", J. Geophys. Res., 94(D6): 8485-8490.

DeLuisi, J.J. and J.M. Harris (1983): "A Determination of the Absolute Radiant Energy of a Robertson-Berger Meter Sunburn Unit", Atmos. Environ., 17(4): 751-758.

Justus, C.G., M.V. Paris and J.D. Tarpley (1986): "Satellite-Measured Insolation in the United States, Mexico and South America", Remote Sens. Environ., 20: 57-83.

Liu, S.C., S.A. McKeen and S. Madronich (1991): "Effect of Anthropogenic Aerosols on Biologically Active Ultraviolet Radiation", Geophys. Res. Lett., 18(12): 2265-2268.

Machta, L. and W.A. Hass (1978): "Summary of Discussion of UV-B from the Robertson-Berger (R/B) Sunburn Meter Network", unpublished manuscript, presented at Climatic Impact Assessment Program meeting, September 22.

Molina, L.T. and M.J. Molina (1986): "Absolute Absorption Cross Sections of Ozone in the 185- to 350-nm Wavelength Range", J. Geophys. Res., 91(D13): 14,501-14,508.

Paris, M.V. and C.G. Justus (1988): "A Cloudy-Sky Radiative Transfer Model Suitable for Calibration of Satellite Sensors", Remote Sens. Environ., 24: 269-285.

Paur, R.J. and A.M. Bass (1985): "The Ultraviolet Cross-Sections of Ozone: II. Results and Temperature Dependence", Proceedings of the Quadrennial Ozone Symposium, Halkidiki, Greece, 3-7 September, 1984, C.S. Zerefos and A.Ghazi, eds., 611-616.

Scotto, J. et al. (1989): "Biologically Effective Ultraviolet Radiation: Surface Measurements in the United States", 1974 to 1985, Science, 239: 762-764.

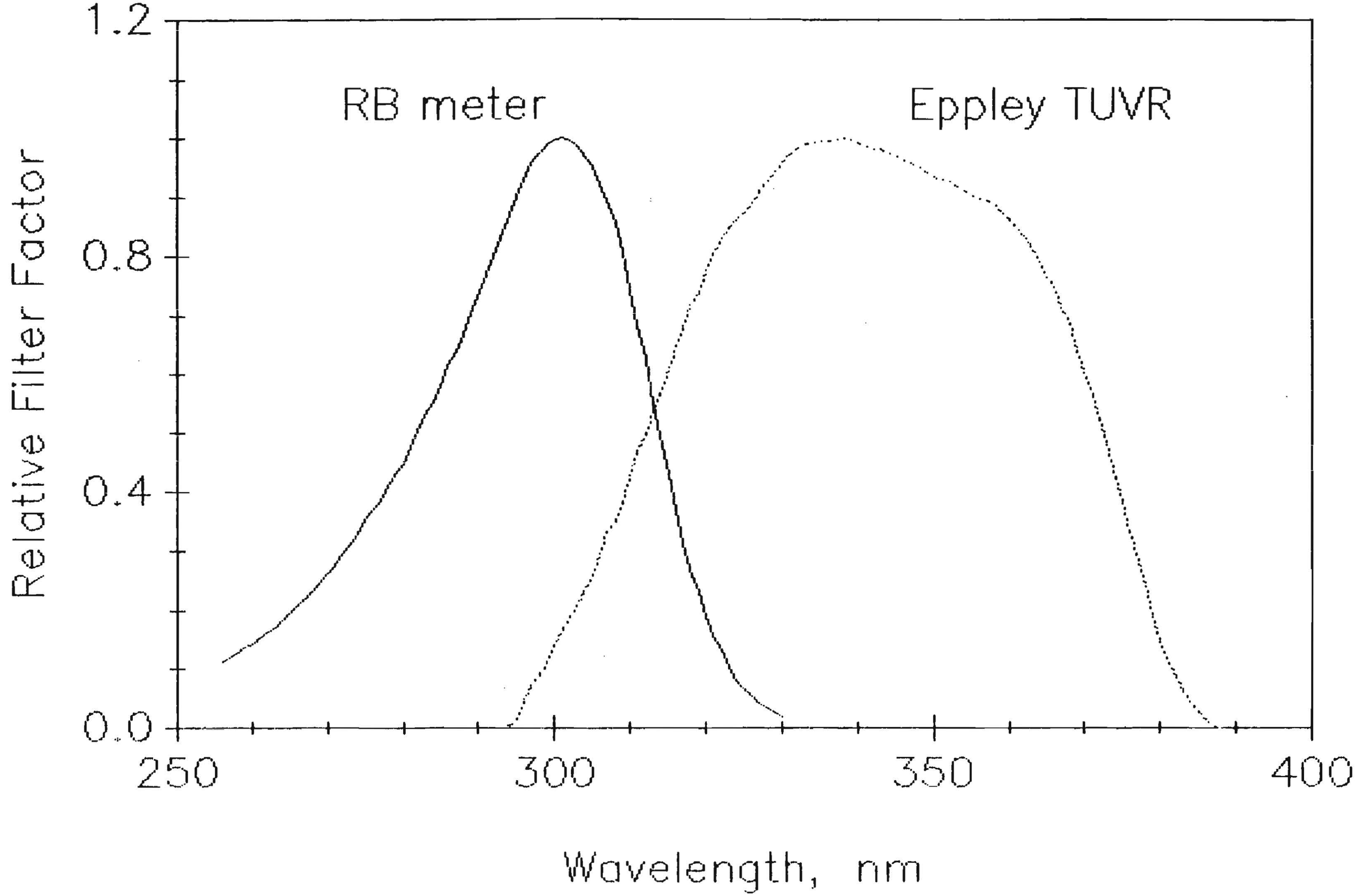

Figure 1 - Relative filter factors for the Robertson-Berger (RB) meter and the Eppley TUVR instruments.

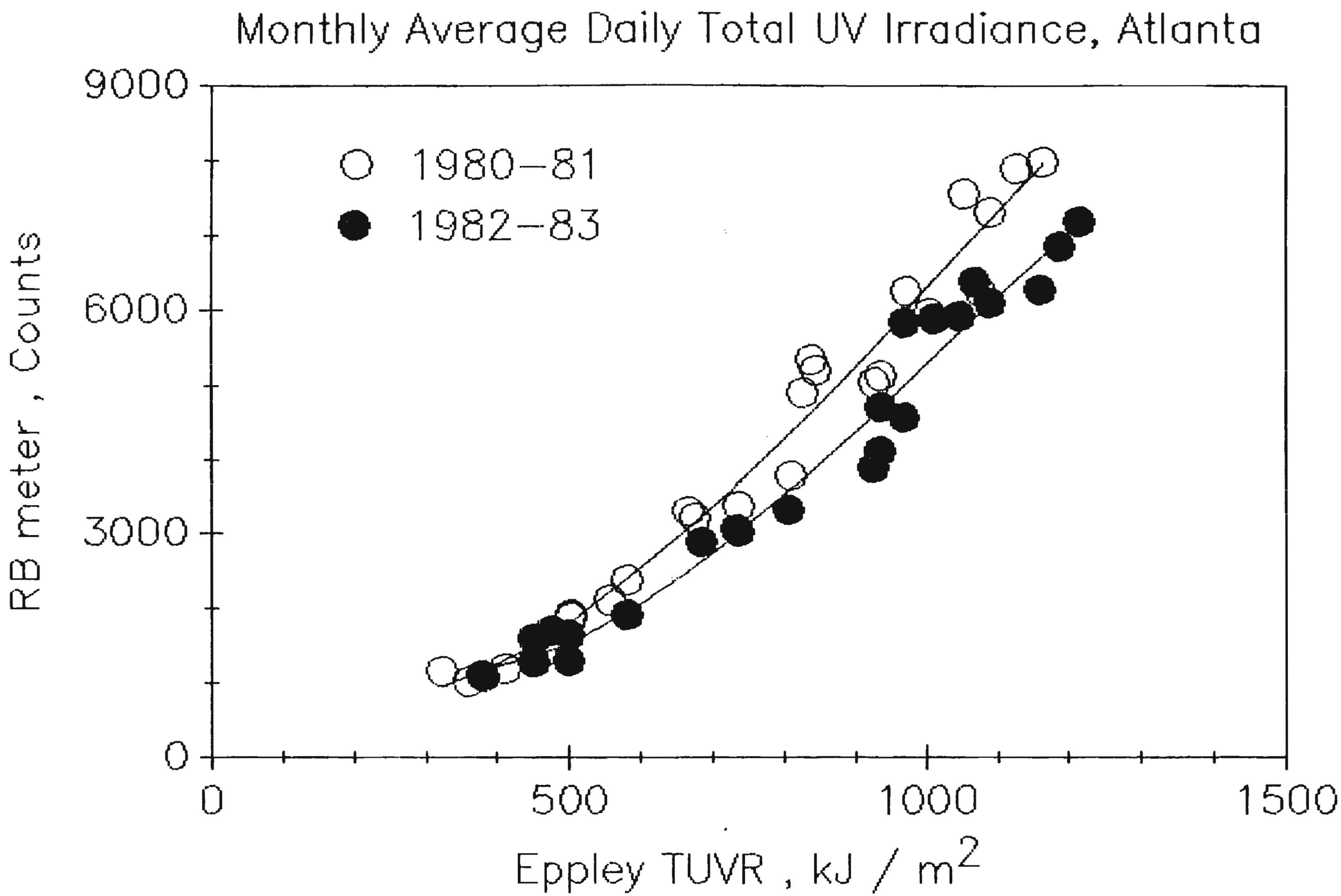

Figure 2 - Observed monthly averaged, daily total UV irradiances observed in Atlanta, from the RB meter and TUVR. Open circles are for months in 1980-81; solid dots are for months in 1982-83.

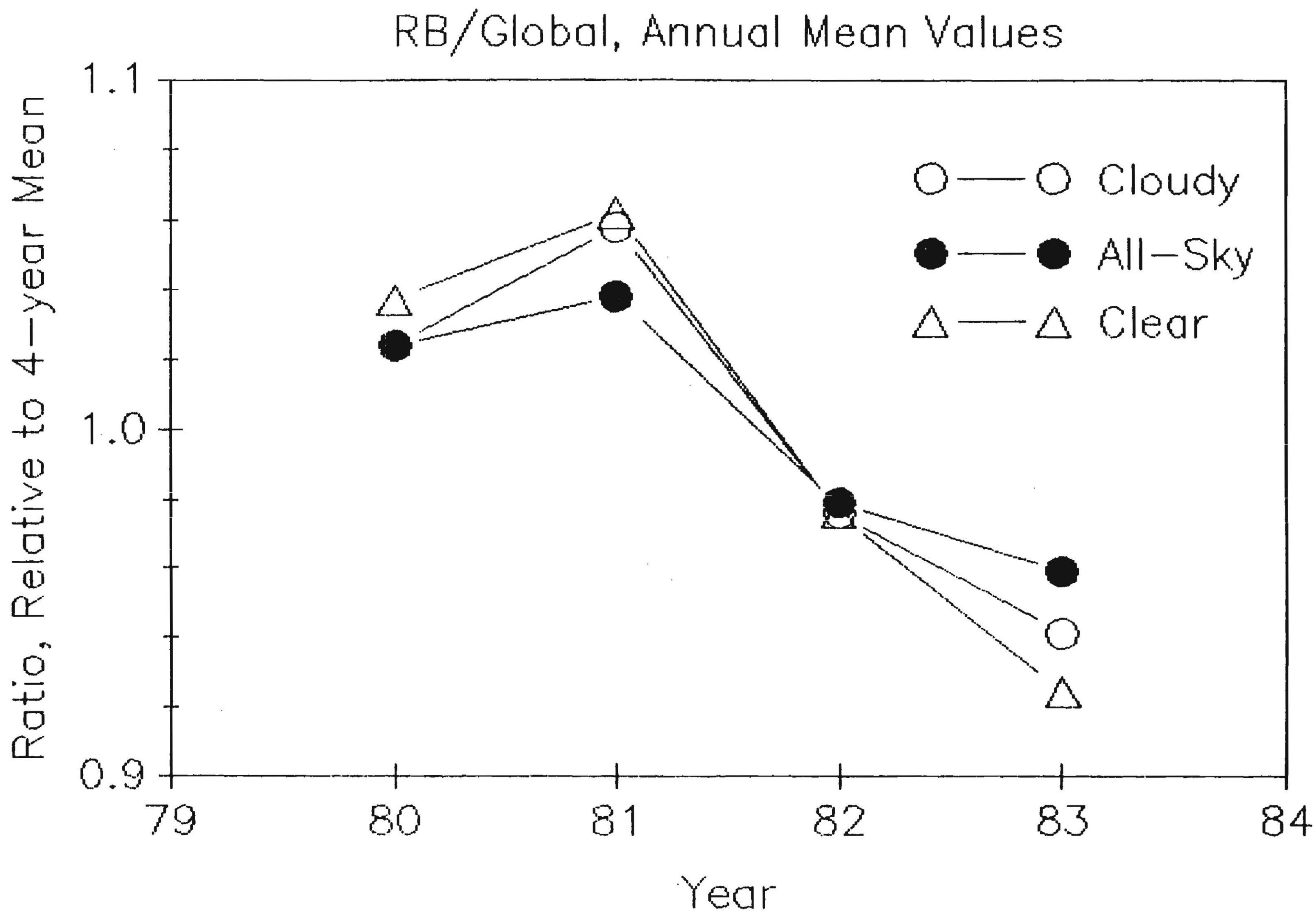

Figure 3 - Trend in RB/Global irradiance ratio (normalized by the 4-year average value of this ratio) for years 1980-83. Triangles are for clear-sky days; open circles are for overcast days; solid dots are all-sky data.

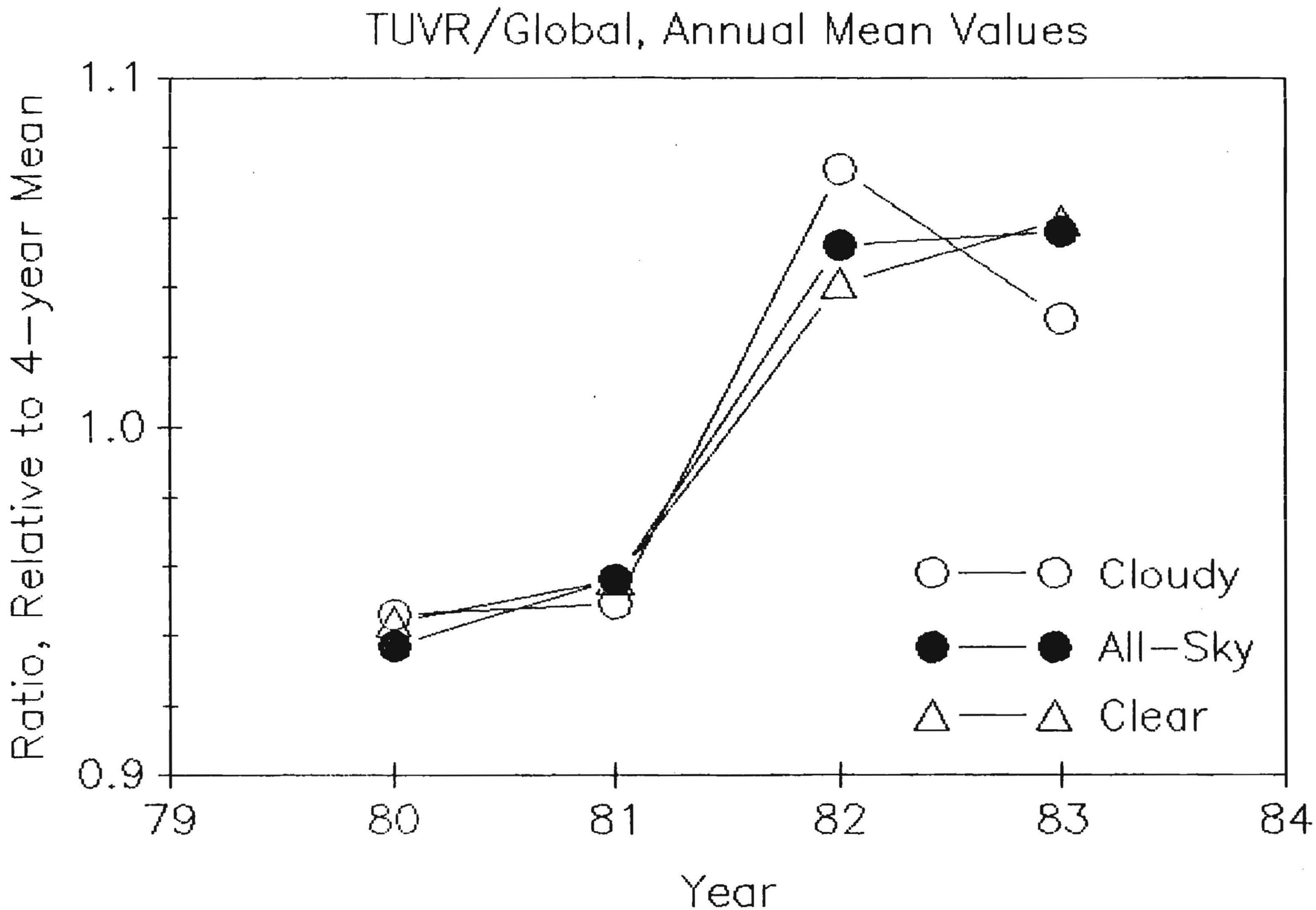

Figure 4 - Trend in TUVR/Global irradiance ratio (normalized by the 4-year average value of this ratio) for years 1980-83. Triangles are for clear-sky days; open circles are for overcast days; solid dots are all-sky data.

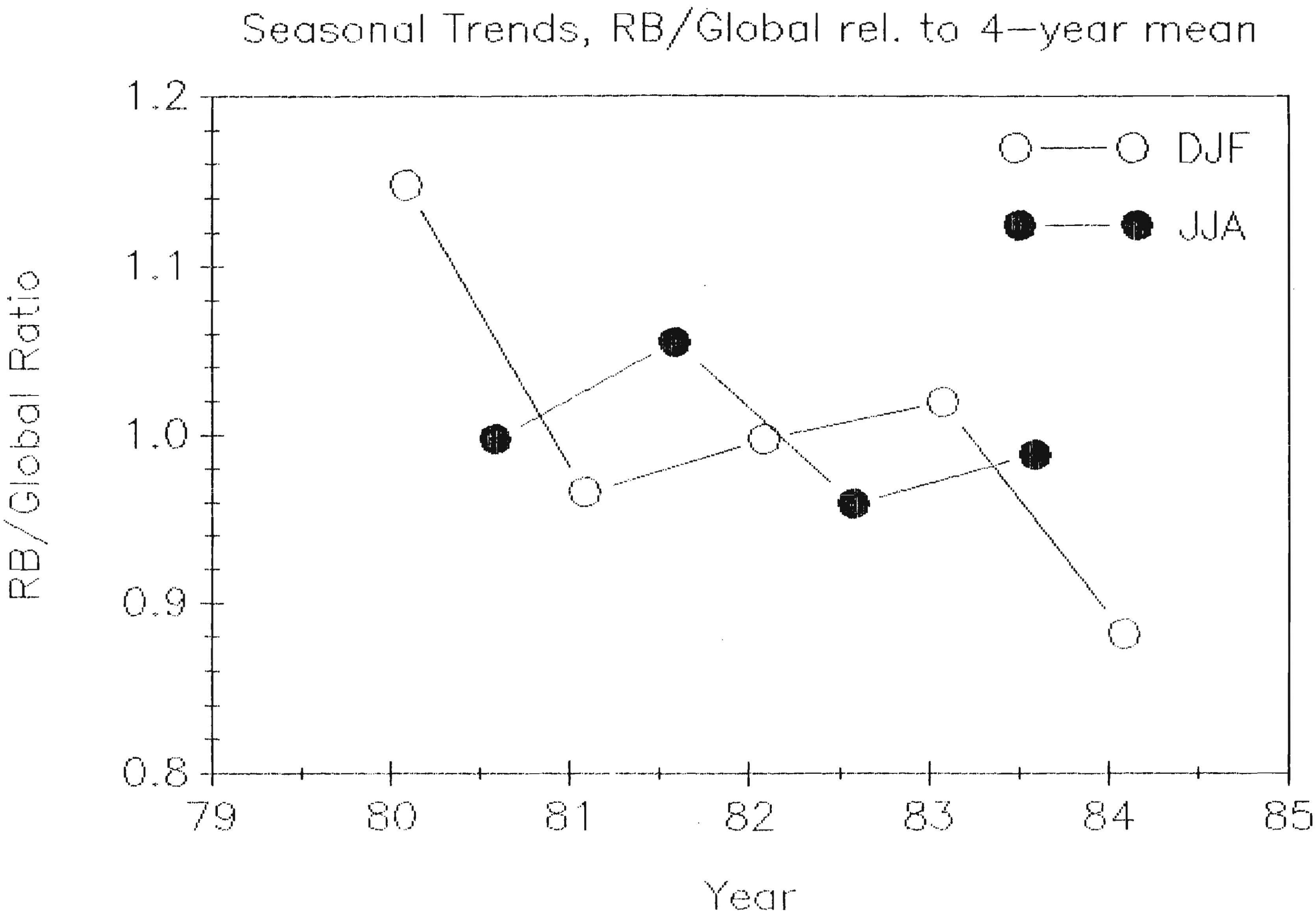

Figure 5 - Trend in RB/Global irradiance ratio (normalized by the 4-year average value of this ratio) for winter (Dec.-Jan.-Feb.) and summer (Jun.-Jul.-Aug.) seasons for years 1980-84.

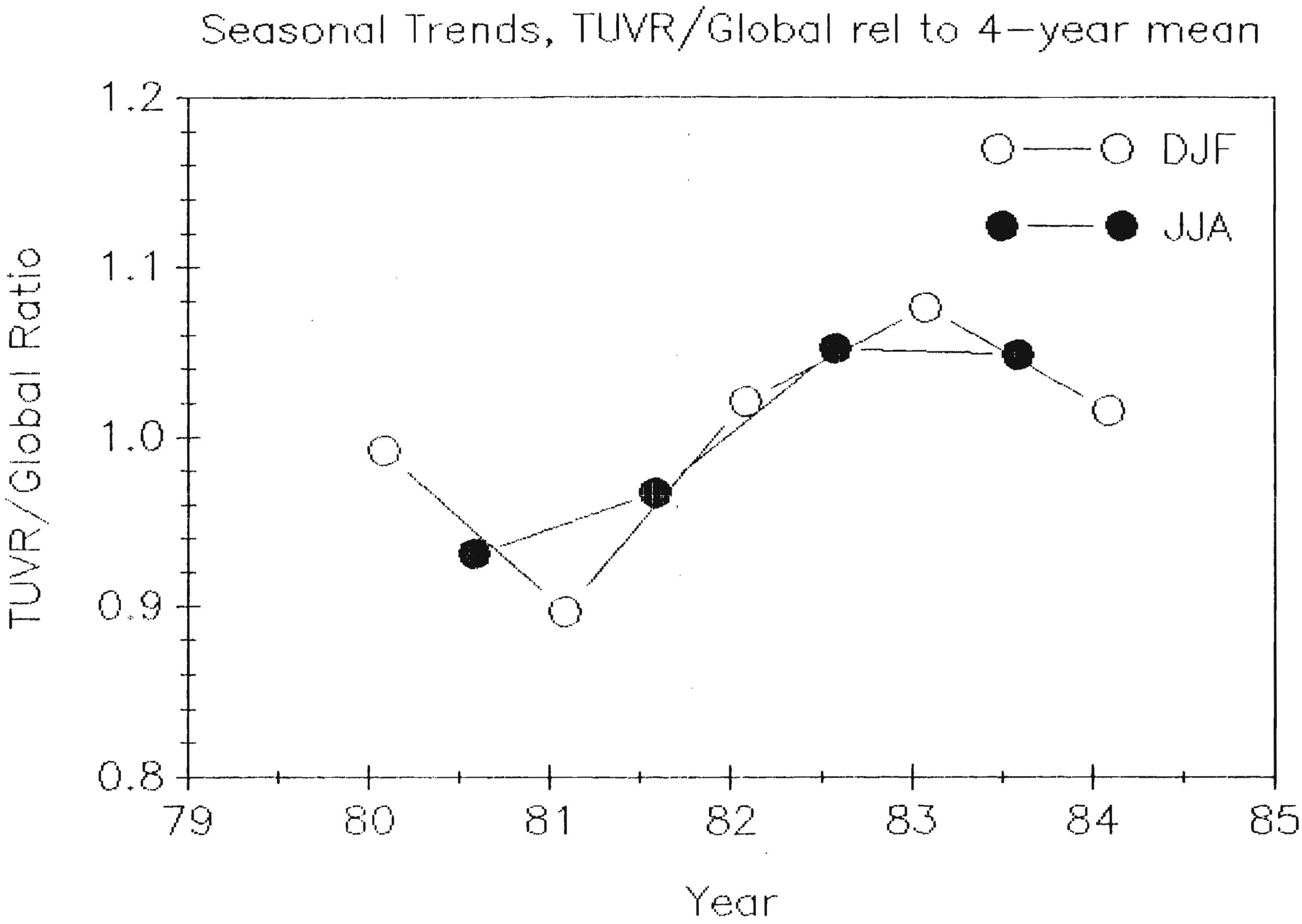

Figure 6 - Trend in TUVR/Global irradiance ratio (normalized by the 4-year average value of this ratio) for winter (Dec.-Jan.-Feb.) and summer (Jun.-Jul.-Aug.) seasons for years 1980-84.

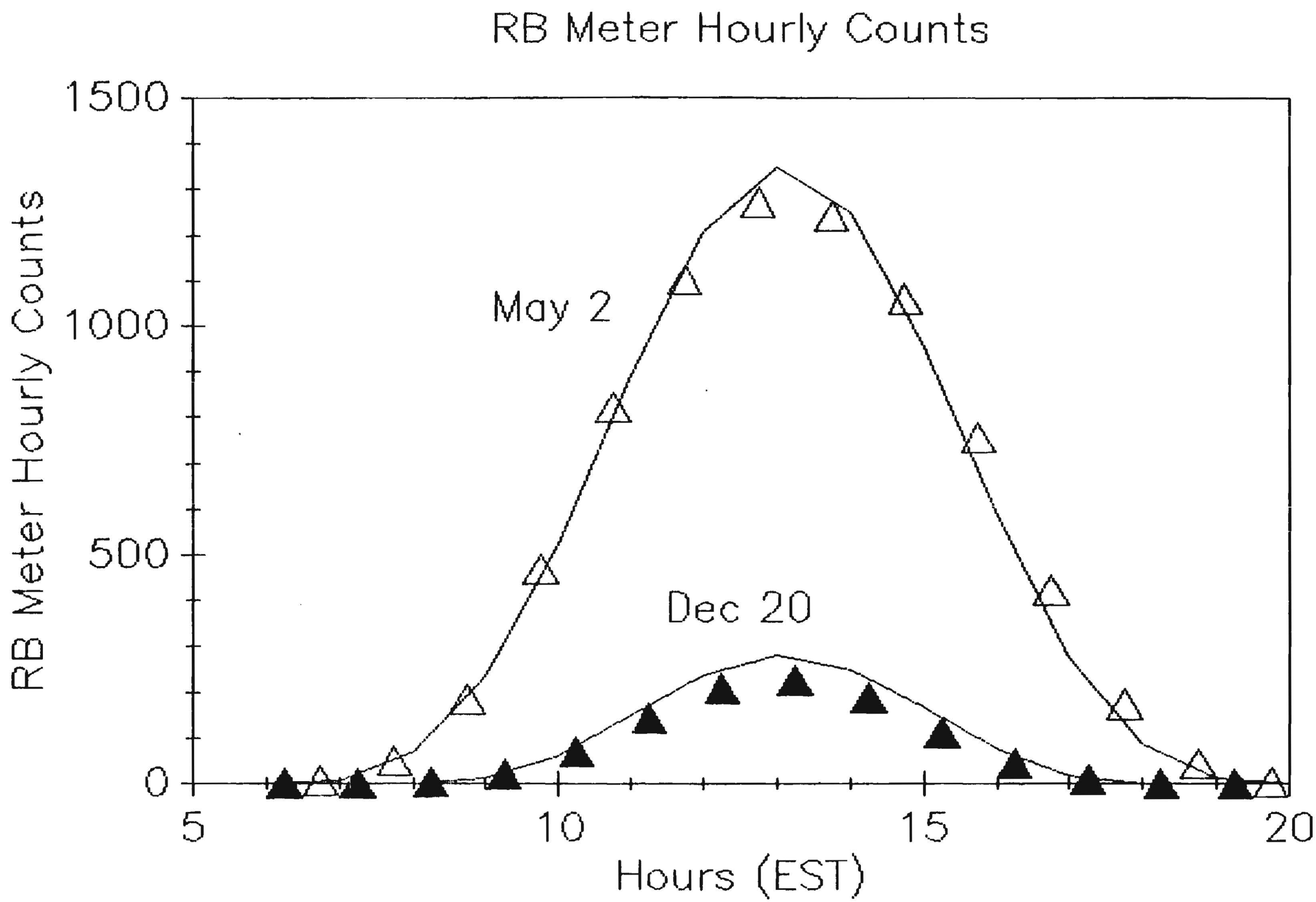

Figure 7 - Observed (symbols) and modeled (lines) values of RB meter hourly irradiances for clear days May 2 and December 20, 1981.

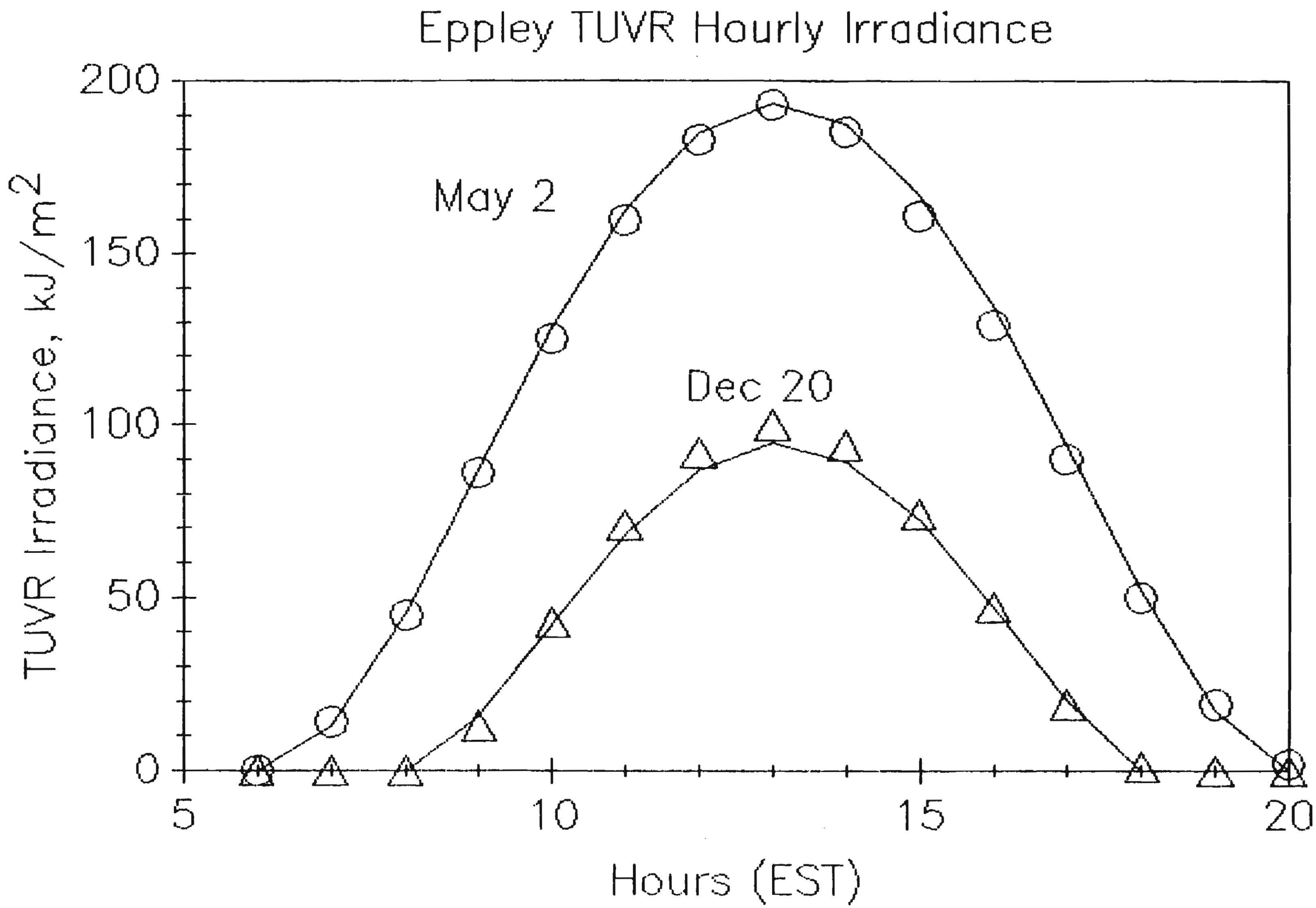

Figure 8 - Observed (symbols) and modeled (lines) values of TUVR hourly irradiances for clear days May 2 and December 20, 1981.

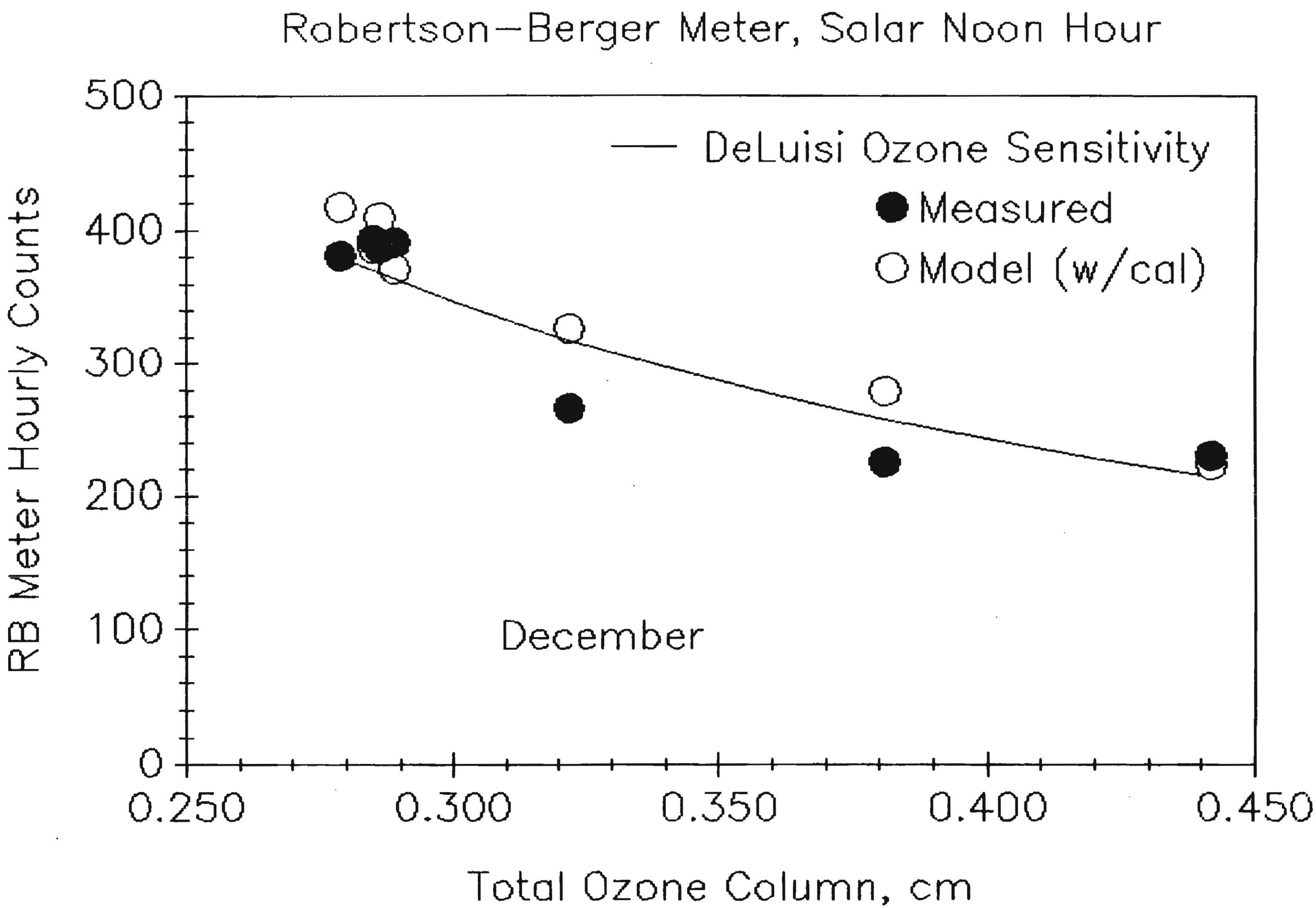

Figure 9 - Observed (solid dots) and modeled (open circles) sensitivity of RB meter hourly irradiances to changes in total column ozone amount. The solid line is the observed ozone sensitivity for the RB meter, determined by DeLuisi and Harris (1983).

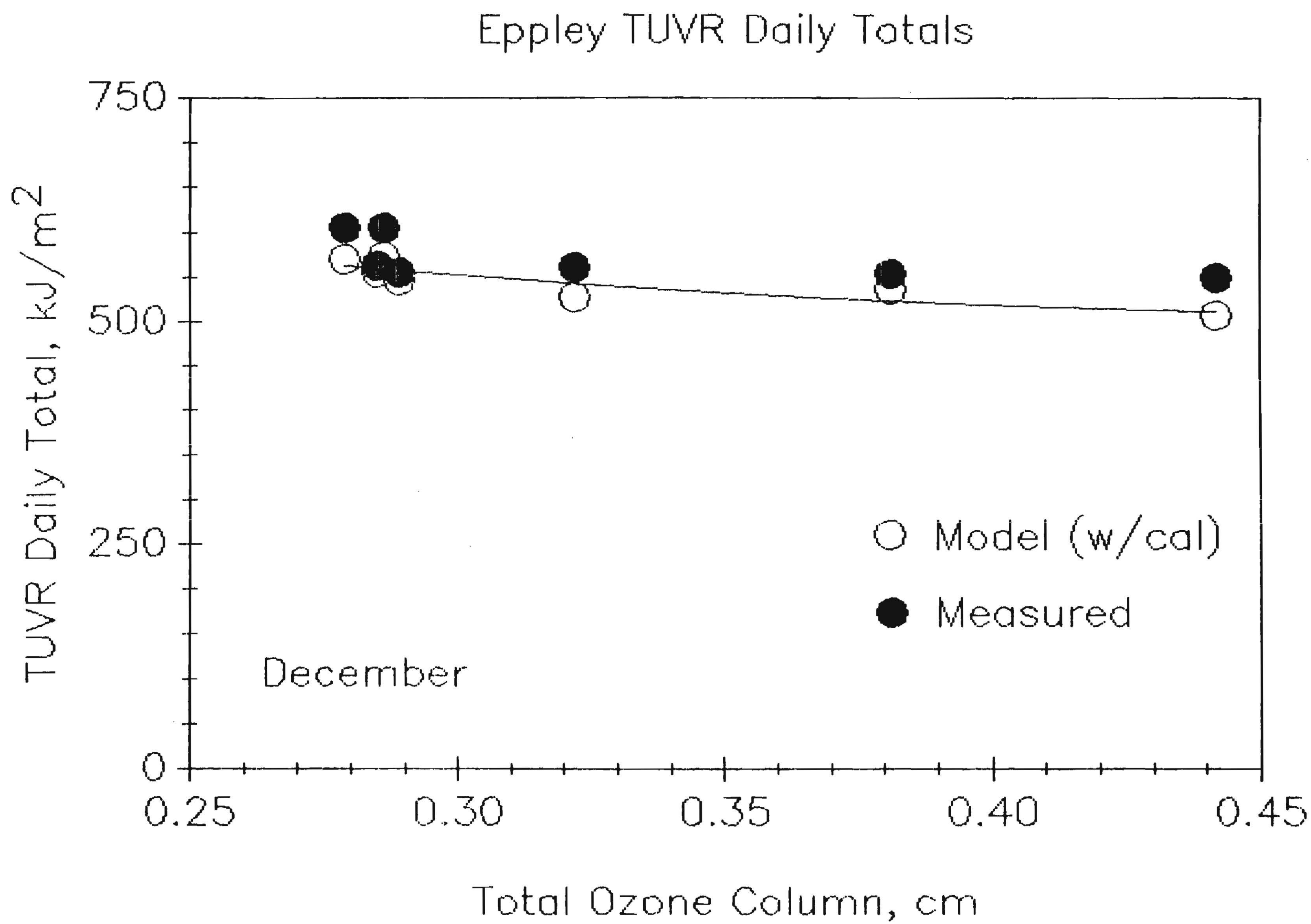

Figure 10 - Observed (solid dots) and modeled (open circles) sensitivity of TUVR daily total irradiances to changes in total column ozone amount. The solid line is the best quadratic fit to the modeled values.

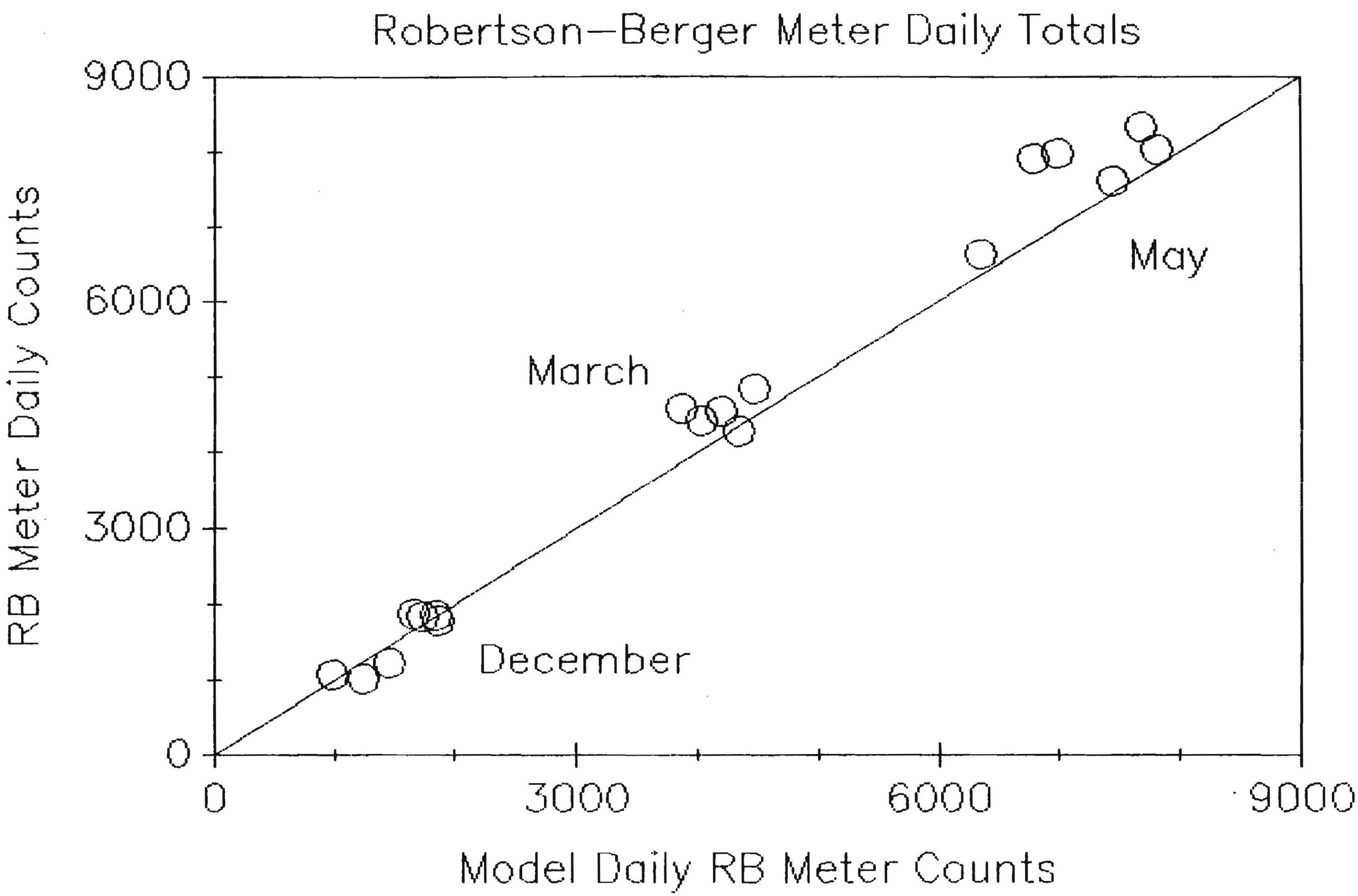

Figure 11 - Observed versus modeled daily total RB meter irradiances. The solid line shows a one-to-one relationship.

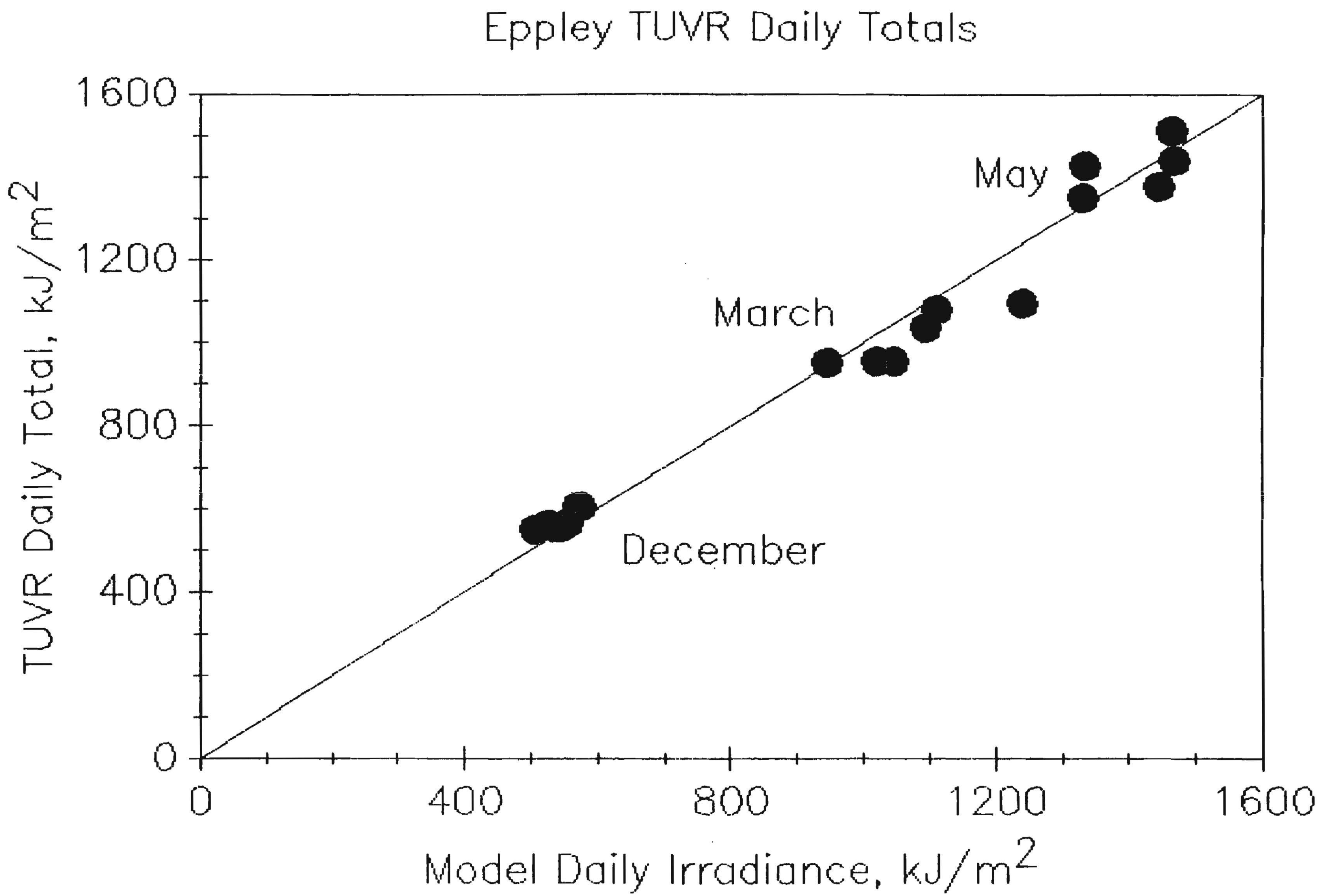

Figure 12 - Observed versus modeled daily total TUVR irradiances. The solid line shows a one-to-one relationship.

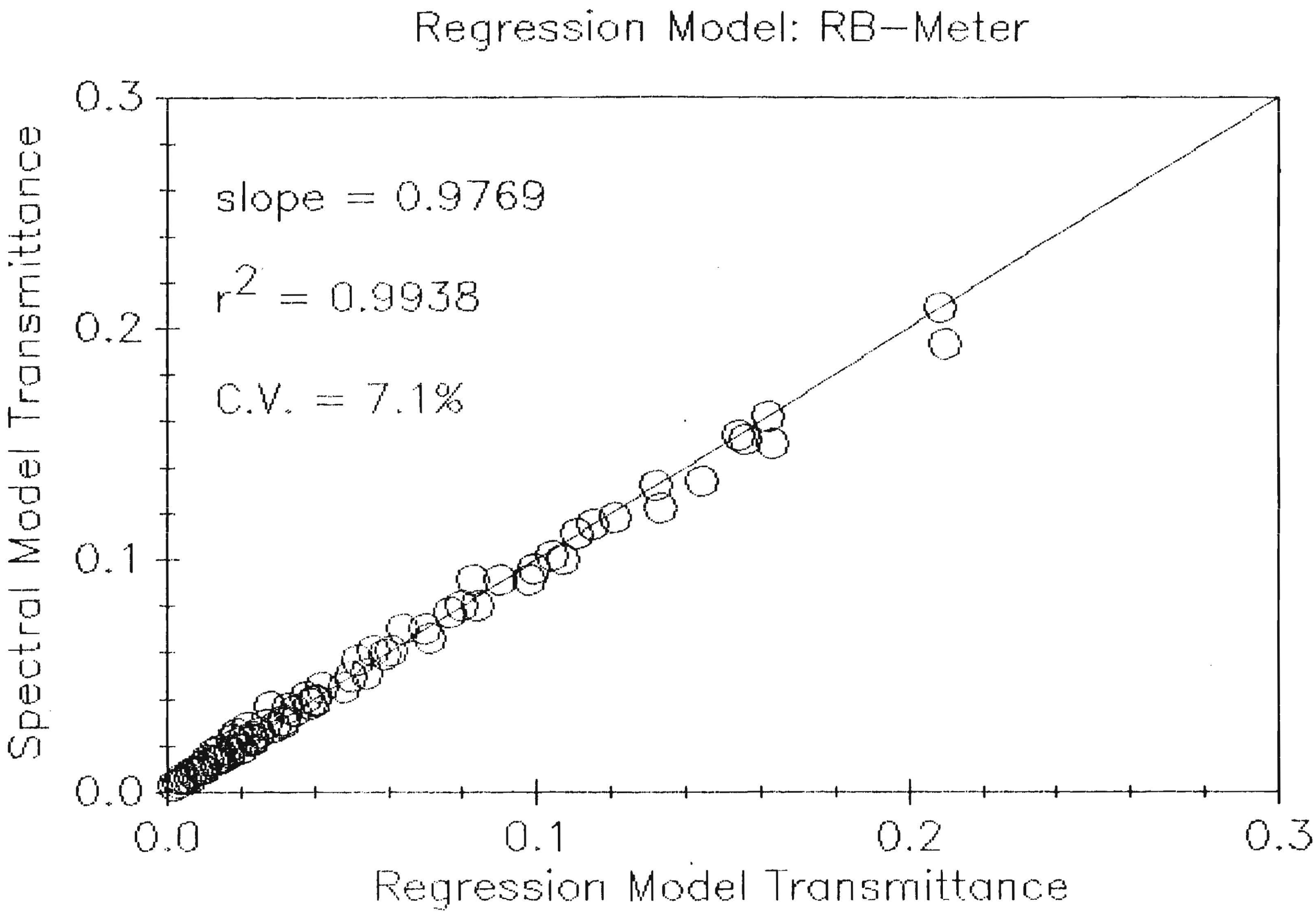

Figure 13 - Comparison of RB-meter transmittance to the surface, as estimated by the rbflux algorithm and as computed by the spectral model for a range of solar zenith angles, ozone amounts and cloud optical depths.

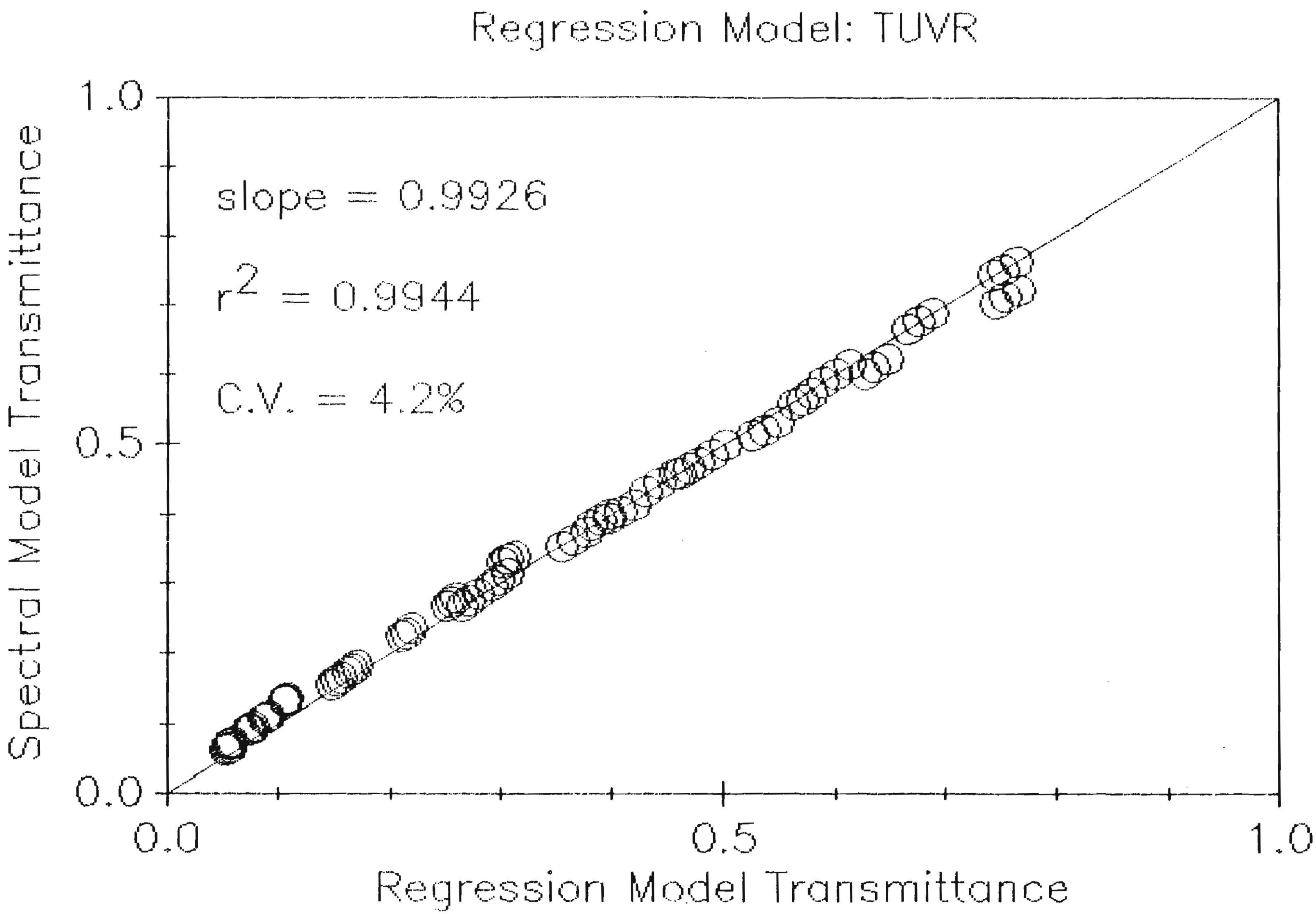

Figure 14 - Comparison of Eppley TUVR transmittance to the surface, as estimated by the tuvrflux algorithm and as computed by the spectral model for a range of solar zenith angles, ozone amounts and cloud optical depths.

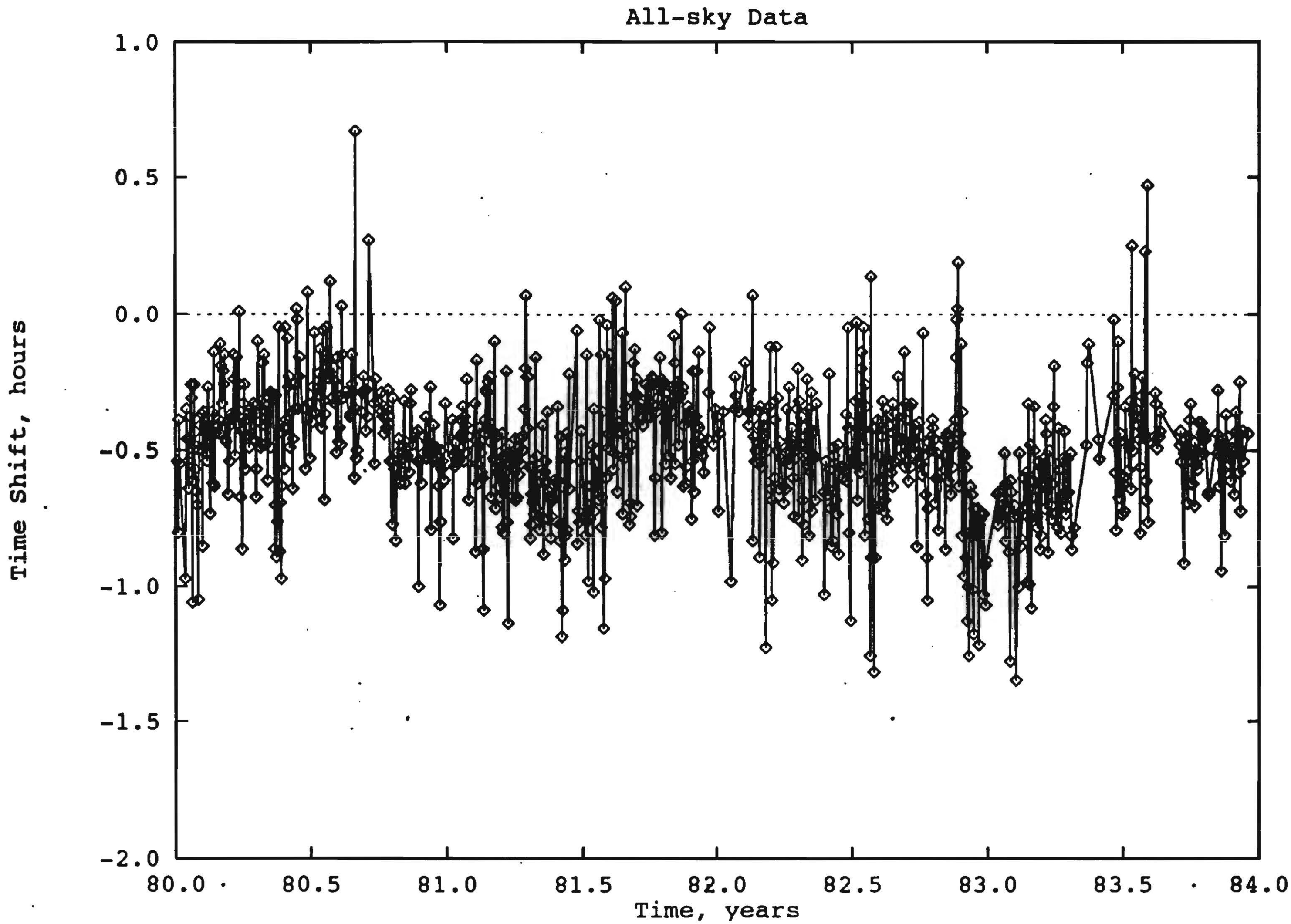

Figure 15 - Temporal variation in the time shift required to maximize the daily cross-correlation between the RB-meter (half hourly) and the Eppley TUVR (hourly) data at Atlanta (Georgia Tech) for the 1980-84 time period.

Table 1. Average daily total global irradiance, number of days analyzed, and average sunshine duration for years 1980-83.

Year	Global Daily Irradiance, kJ/m^2 Cloudy	All-Sky	Clear	Number of Days Analyzed Cloudy	All-Sky	Clear	Avg. Sunshine Duration %
1980	4104	15,332	18,236	49	243	51	50
1981	4523	15,765	19,183	49	272	54	53
1982	3564	13,886	18,639	57	247	27	44
1983	4380	13,920	17,307	43	201	34	47
AVG	4143	14,726	18,341	50	241	42	49

Table 2. Average daily total Robertson-Berger meter counts, and average daily Eppley TUVR Irradiance for years 1980-1983.

Year	RB Meter Daily Counts Cloudy	All-Sky	Clear	TUVR Daily Irradiance, kJ/m^2 Cloudy	All-Sky	Clear
1980	1200	4127	3940	265	747	839
1981	1367	4303	4246	293	783	894
1982	993	3571	3791	261	759	945
1983	1177	3508	3334	308	764	893
AVG	1184	3877	3828	282	763	893

Table 3. Ratios (RB meter/Global) and (TUVR/Global), from data in Tables 1 and 2.

Year	RB/Global, counts $kJ^{-1}m^2$			TUVR/Global, unitless		
	Cloudy	All-Sky	Clear	Cloudy	All-Sky	Clear
1980	0.2924	0.2692	0.2161	0.0646	0.0487	0.0460
1981	0.3022	0.2729	0.2213	0.0648	0.0497	0.0466
1982	0.2786	0.2572	0.2034	0.0732	0.0547	0.0507
1983	0.2687	0.2520	0.1926	0.0703	0.0549	0.0516
AVG	0.2855	0.2628	0.2084	0.0682	0.0520	0.0487

APPENDIX

Fortran Source Code for the RB-Meter and TUVR Surface Irradiance Algorithms

```
      Function rbflux(za,rpg,rpg0,oz,E0)
C...  Computes surface downwelling RB-meter filter-band irradiance
C     (W/m**2/um), from the solar zenith angle (za, degrees), the
C     GOES visible-band reflectance (rpg), the clear-sky GOES visible-
C     band reflectance (rpg0), the total ozone column (atm. cm), and
C     the RB-meter filter-band extra-terrestrial solar irradiance
C     on a horizontal surface (E0, W/m**2/um).
C.................................................................
C
C...  Coefficients for clear-sky transmittance at 0.2 atm. cm ozone
      Parameter (a200 = -0.8357E-3, b200 = 0.2388, c200 = -.02890)
C...  Coefficients for clear-sky transmittance at 0.3 atm. cm ozone
      Parameter (a300 = -0.4362E-2, b300 = 0.1718, c300 = -.5217E-2)
C...  Coefficients for clear-sky transmittance at 0.4 atm. cm ozone
      Parameter (a400 = -0.5466E-2, b400 = 0.1299, c400 = .7805E-2)
C...  Coefficients of Thalf parameter used in the cloud-modifier term
      Parameter (c0half = 0.356, c1half = 0.123)
C...  Coefficients in the rinf cloud-modifier factor
      Parameter (c0r = .9111, c1r = -.1503E-2, c2r = -.4451E-2,
     &    c3r = .4308E-3)
C...  Factors for angle conversion
      pi = 4.*atan(1.)
      pi180 = pi/180.
C...  tthet = tangent of solar zenith angle
      tthet = tan(pi180*za)
C...  cthet = cosine of solar zenith angle
      cthet = cos(pi180*za)
C...  T200,T300,T400 = clear-sky transmittance at 0.2,0.3,0.4 atm cm
C     ozone
      T200 = a200 + b200*cthet + c200*cthet**2
      T300 = a300 + b300*cthet + c300*cthet**2
      T400 = a400 + b400*cthet + c400*cthet**2
C...  Toz = clear-sky transmittance at observed ozone amount
      aoz = (T400 - T200)/0.2
      boz = (T400 + T200 - 2.*T300)/0.02
      Toz = T300 + aoz*(oz - 0.3) + boz*(oz - 0.3)**2
C...  rinf = GOES visible-band reflectance at infinite cloud optical
C     depth
      rinf = c0r + c1r*tthet + c2r*tthet**2 + c3r*tthet**3
C...  Rnorm = normalized GOES visible-band reflectance
      Rnorm = (rpg - rpg0)/(rinf - rpg0)
C...  anorm, bnorm = coefficients for cloud-modifier term
      Thalf = c0half + c1half*cthet
      anorm = 4.*Thalf - 1.
      bnorm = 1. - anorm
C...  Compute Tnorm = normalized RB-meter filter-band transmittance
      Tnorm = anorm*Rnorm + bnorm*Rnorm**2
```

```
C...  Compute RB-meter filter-band transmittance, T, from normalized
C     transmittance
      Trans = Toz*(1. - Tnorm)
C...  Compute RB-meter surface irradiance from transmittance
      rbflux = E0*Trans
      Return
      End
```

```
      Function tuvrflux(za,rpg,rpg0,oz,E0)
C...  Computes surface downwelling TUVR-meter filter-band irradiance
C     (W/m**2/um), from the solar zenith angle (za, degrees), the
C     GOES visible-band reflectance (rpg), the clear-sky GOES visible-
C     band reflectance (rpg0), the total ozone column (atm. cm), and
C     the TUVR-meter filter-band extra-terrestrial solar irradiance
C     on a horizontal surface (E0, W/m**2/um).
C.....................................................................
C
C...  Coefficients for clear-sky transmittance at 0.2 atm. cm ozone
      Parameter (a200 = .3558, b200 = 0.6186, c200 = -.2111)
C...  Coefficients for clear-sky transmittance at 0.3 atm. cm ozone
      Parameter (a300 = .3393, b300 = 0.6288, c300 = -.2168)
C...  Coefficients for clear-sky transmittance at 0.4 atm. cm ozone
      Parameter (a400 = .3279, b400 = 0.6273, c400 = -.2131)
C...  Coefficients of Thalf parameter used in the cloud-modifier term
      Parameter (c0half = 0.328, c1half = 0.137)
C...  Coefficients in the rinf cloud-modifier factor
      Parameter (c0r = .9111, c1r = -.1503E-2, c2r = -.4451E-2,
     &     c3r = .4308E-3)
C...  Factors for angle conversion
      pi = 4.*atan(1.)
      pi180 = pi/180.
C...  tthet = tangent of solar zenith angle
      tthet = tan(pi180*za)
C...  cthet = cosine of solar zenith angle
      cthet = cos(pi180*za)
C...  T200,T300,T400 = clear-sky transmittance at 0.2,0.3,0.4 atm cm
C     ozone
      T200 = a200 + b200*cthet + c200*cthet**2
      T300 = a300 + b300*cthet + c300*cthet**2
      T400 = a400 + b400*cthet + c400*cthet**2
C...  Toz = clear-sky transmittance at observed ozone amount
      aoz = (T400 - T200)/0.2
      boz = (T400 + T200 - 2.*T300)/0.02
      Toz = T300 + aoz*(oz - 0.3) + boz*(oz - 0.3)**2
C...  rinf = GOES visible-band reflectance at infinite cloud optical
C     depth
      rinf = c0r + c1r*tthet + c2r*tthet**2 + c3r*tthet**3
C...  Rnorm = normalized GOES visible-band reflectance
      Rnorm = (rpg - rpg0)/(rinf - rpg0)
C...  anorm, bnorm = coefficients for cloud-modifier term
      Thalf = c0half + c1half*cthet
      anorm = 4.*Thalf - 1.
      bnorm = 1. - anorm
C...  Compute Tnorm = normalized TUVR-meter filter-band transmittance
      Tnorm = anorm*Rnorm + bnorm*Rnorm**2
C...  Compute TUVR-meter filter-band transmittance, T, from normalized
C     transmittance
      Trans = Toz*(1. - Tnorm)
C...  Compute TUVR-meter surface irradiance from transmittance
      tuvrflux = E0*Trans
      Return
      End
```